THE LEAF MESOPHYLLS OF TWENTY CROPS, THEIR LIGHT SPECTRA, AND OPTICAL AND GEOMETRICAL PARAMETERS

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PREFACE

The present work was undertaken to make a systematic comparison of the optical behavior and mesophyll structures for leaves of 20 plant genera. The genera selected represent plants that are important in both temperate and tropical climates.

The authors are unaware of any other reference in which such extensive absolute radiometric data, optical constants, geometric parameters, and leaf structure information is assembled. The authors trust that the information presented will find application among plant breeders; researchers interested in photosynthesis, plant water relations, and water and energy conservation; botanists and taxonomists--as well as those in remote sensing who are interested in finding uniqueness in the optical spectra of various crops.

This Research Report is intended to be a temporary publication. The data are expected to be published in a more permanent and citeable form, possibly as a Technical Monograph of the Texas Agricultural Experiment Station. It will be approximately a year before such reprints are available.

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SUMMARY

Leaf mesophylls among 20 agricultural crops are compared with: (1) spectrophotometrically measured percent reflectances and transmittances, and calculated absorptances of the leaves over the 500- to 2500-nanometer (nm) wavelength interval (WLI), (2) percent leaf water (H_2O) contents, (3) leaf thickness measurements, and (4) optical and geometrical leaf parameters. Data are given as averages of 10 leaves (replications) for each crop. The crops with their corresponding scientific names are:

Avocado	*Persea americana* Mill.
Bean	*Phaseolus vulgaris* L.
Cantaloupe	*Cucumis melo* L. var. *cantalupensis* Naud.
Corn	*Zea mays* L.
Cotton	*Gossypium hirsutum* L.
Lettuce	*Lactuca sativa* L.
Okra	*Hibiscus esculentus* L.
Onion	*Allium cepa* L.
Orange	*Citrus sinensis* (L.) Osbeck
Peach	*Prunus persica* (L.) Batsch
Pepper	*Capsicum annuum* L. and other spp.
Pigweed	*Amaranthus retroflexus* L.
Pumpkin	*Cucurbita pepo* L.
Sorghum	*Sorghum bicolor* (L.) Moench
Soybean	*Glycine max* (L.) Merr.
Sugarcane	*Saccharum officinarum* L.
Sunflower	*Helianthus annuus* L.
Tomato	*Lycopersicon esculentum* Mill.
Watermelon	*Citrullus lanatus* (Thunb.) Mansf.
Wheat	*Triticum aestivum* L.

H_2O content. Thick, succulent lettuce leaves had the highest H_2O content (97.0%), and dorsiventral avocado, orange, and peach, and compact sugarcane leaves had the lowest H_2O contents (range 60.6 to 72.4%). Compact corn, sorghum, and sugarcane leaves within the family *Gramineae*, and dorsiventral cotton and okra leaves within the family *Malvaceae* had similar H_2O contents.

Leaf thickness. Soybean, peach, pumpkin, and pigweed leaves were thinnest (range .140 to .170 mm) and sunflower, cantaloupe, lettuce, and onion leaves were thickest (range .407 to .978 mm). Within the families *Malvaceae* and *Gramineae*, cotton and okra, and sugarcane and sorghum were alike in leaf thickness.

Leaf thickness was poorly correlated with H_2O content. Highest coefficients accounted for only 31 to 34% (r^2 x 100) of the variation between leaf thicknesses and H_2O contents.

Reflectance, transmittance, and absorptance. Mean reflectances, transmittances, and absorptances for the 550-, 800-, 1000-, 1450-, 1650-, 1950-, and 2200-nm wavelengths (WL) were compared using Duncan's Multiple Range Test. Onion and bean leaves had the lowest (18.1%) and highest (31.6%) reflectances, respectively. Orange leaves had the lowest transmittance (20.4%) and soybean leaves had the highest transmittance (34.9%). Among the 20 crops, onion leaves had the highest absorptance of 57.4%, and sorghum and soybean leaves as a group had the lowest absorptances (36.7 to 36.9%).

The reflectances, transmittances, and absorptances of bean, avocado, sorghum, and pigweed leaves are portrayed in the text for the 500- to 2500-nm WLI. The reflectances, transmittances, and absorptances of the remaining 16 crops are portrayed only in the Appendix. The data (average of 10 replications) for the reflectance, transmittance, and absorptance of leaves for each crop at each of the 41 wavelengths are tabulated in Appendix Tables.

Intensive study was given to the 550- and 1000-nm WL representing the visible (400 to 750 nm) and near-infrared (750 to 1350 nm) spectral regions, respectively. Data for lettuce leaves were omitted because the leaves sampled from the head of lettuce were immature.

550 nm. The mean reflectance of the crop leaves at the 550-nm WL was 13.3% ± 2.8% (one standard deviation). The majority of crops fell within the 13.3% ± 2.8% range except avocado and orange (8.9 and 10.2%, respectively), and corn, pepper, sorghum, bean, and sugarcane leaves (16.2 to 18.6%). High reflectances are indicative of low chlorophyll contents, and conversely low reflectances are indicative of high chlorophyll contents.

At the 550-nm WL, transmittances of orange, tomato, and avocado (1.9 to 5.5%) and okra, soybean, onion (14.8 to 18.8%) fell outside the 9.8% ± 4.2% range. In general, the spectral transmittance curves for all mature and healthy leaves were similar to their spectral reflectance curves over the 500- to 2500-nm WLI, but slightly lower in magnitude.

The mean absorptance for the crops at 550-nm WL was 76.9% ± 5.8%. Thirteen crops fell within the 76.9% ± 5.8% range. Sugarcane, onion, bean, and pepper leaves with low absorptance (69.2 to 70.6%) and peach, tomato, avocado, and orange leaves with high absorptance (82.9 to 87.9%) fell outside the 76.9% ± 5.8% range. The leaves with high absorptance had well-differentiated dorsiventral mesophylls with many chloroplasts in their palisade cells. Leaves with low absorptance had poorly differentiated mesophylls--less distinction between palisade and spongy parenchyma cells.

1000 nm. The 1000-nm WL can be used to evaluate the influence of leaf mesophyll arrangement on near-infrared (750 to 1350 nm) light reflectance. The mean reflectance of the crop leaves at the 1000-nm WL was 48.0% ± 3.9%. The reflectance of onion (38.5%) and orange and bean (55.6 and 56.2%, respectively) fell outside the 48.0% ± 3.9% range. However, only one-half of the tubular onion leaf (split longitudinally) was used for spectrophotometric measurements. Thus, discounting onion as an unusual leaf, compact pigweed, corn, sugarcane, and sobyean leaves had the lowest reflectances (45.1 to 46.0%), and dorsiventral bean, orange, and pepper leaves with very porous mesophylls had the highest reflectances (51.0 to 56.2%). A leaf with a compact mesophyll has lower light reflectance (fewer cell wall-air space interfaces for light refraction) and concomitantly higher transmittance than a leaf with a porous mesophyll.

At the 1000-nm WL, the mean transmittance of all crop leaves was 47.9% ± 3.7%. All crops fell within this range except orange and bean (38.9 and 42.0%, respectively) and soybean, pigweed, and onion (52.2 to 54.0%).

The mean absorptance of all crop leaves at the 1000-nm WL was 4.0% ± 1.7%. Soybean and bean leaves (1.8%) and sugarcane, tomato, and onion leaves (6.7 to 7.5%) fell outside the 4.0% ± 1.7% range. Soybean and bean leaves with low absorptance of near-infrared light have very porous mesophylls.

Correlations. Correlation coefficients equal to or larger than ± 0.775 are considered that accounted for at least 60% of the variation (0.775^2 X 100) between leaf thickness and reflectance, leaf thickness and absorptance; leaf H_2O content and reflectance; and leaf H_2O content and absorptance. Negative coefficients exceeding -0.775 were obtained for correlations between light reflectance and percent leaf H_2O content for sugarcane at 1450-, 1650-, and 2200-nm, for corn at 550- and 1450-nm; for pigweed at 1450-nm; and for tomato at 1450- and 2200-nm WL. Soybean was the only crop that had positive coefficients exceeding 0.775 for the correlation between reflectance and leaf thickness at the 550-, 800-, and 1000-nm WL, and a negative coefficient that exceeded -0.775 for the correlation between transmittance and leaf thickness at the 1000-nm WL. Soybean leaves also had large negative coefficients for the correlation between reflectance and leaf thickness at the 1450-, 1950-, and 2200-nm WL, and for the correlation between transmittance and leaf thickness at the 1450-, 1650-, 1950-, and 2200-nm WL. Peach, pigweed, tomato, bean, and onion crops also had high negative coefficients for the correlation between transmittance and leaf thickness at two or more of the 1450-, 1650-, 1950-, and 2200-nm WL. High positive coefficients were obtained for the correlation between leaf thickness and percent light absorptance for the soybean, peach, pigweed, bean, and onion crops at three or more of the 1450-, 1650-, 1950-, and 2200-nm WL.

It was thought that the amount of H_2O in the leaf tissue placed over the port of the spectrophotometer might have influenced the spectral energy measurements. Accordingly, g of H_2O/cm^3 of leaf tissue was calculated for each crop leaf used in this study, except wheat. There was no correlation between reflectance and g of H_2O/cm^3 of leaf tissue. For transmittance, coefficients that exceeded -0.775 occurred only with okra leaves at 1000-, 1450-, 1650-, 1950-, and 2200-nm WL. The correlation between absorptance and g of H_2O/cm^3 of leaf tissue gave high positive coefficients for okra leaves at 1450-, 1650-, and 2200-nm. Variability in g of H_2O/cm^3 among okra leaves had an important influence on their light absorptance and transmittance compared with the variability among leaves of the other crops.

Optical and geometrical parameters. Experimental values of leaf reflectance and transmittance for the 20 crops have been transformed into effective optical constants. Such optical constants are useful in the prediction of reflectance phenomena associated with leaves either stacked in a spectrophotometer or arranged naturally in a plant canopy. The index of refraction n is plotted against wavelength to obtain dispersion curves. The values for the absorption coefficient K that are tabulated for the various crops are equivalent to values determined previously for leaves from agricultural crops.

The dispersion curves of most of the crop leaves were remarkably similar. With the exceptions of onion, pigweed, and lettuce, the dispersion curves are characterized by similar shapes and relatively close confidence bands. However, the leaves indicated as exceptions differed from the other crop leaves--only one-half of the tubular onion leaves (split longitudinally) was used; lettuce leaves were immature; and veins of pigweed leaves are surrounded by large, cubical, parenchymatous cells.

Sixteen of the 20 crops have been analyzed to obtain geometrical parameters that specify the amount of H_2O and air in the leaf. The H_2O parameter is the thickness of liquid H_2O necessary to produce the observed leaf absorption. The air parameter is the number of identical compact layers into which the equivalent H_2O must be subdivided to achieve the observed partition of light between reflectance and transmittance. Sugarcane, corn, sorghum, and wheat leaves were not included because laboratory determinations of thickness and H_2O content were not made on entire leaves. There was no statistically significant difference between H_2O obtained experimentally and H_2O determined theoretically for all crops except pumpkin, avocado, okra, tomato, cantaloupe, and lettuce. But none of the six exceptions exhibited a highly significant difference between observed and computed values for leaf water.

The limiting value of reflectance from leaves piled sufficiently deep is characterized by an optical parameter termed infinite reflectance. This parameter is a function of the calculated thickness of the identical compact layers of which a leaf is assumed to be composed. Infinite reflectance has been tabulated at 1.65 μm for the 20 crops.

INTRODUCTION

In order to interpret remote sensing data acquired from aircraft and spacecraft, the reflectance produced by features on the earth's surface must be understood (Wiegand et al., 1969). The specific problem in agriculture is interpretation of reflectance produced by vegetation, usually superimposed upon a soil background. Plant leaves yield most of the signal measured by remote sensors in aircraft and spacecraft and are therefore of prime interest in characterizing vegetation. Therefore, their interaction with electromagnetic radiation must be understood.

The purpose of research reported here was to relate the leaf mesophyll structure of 20 important agricultural plant genera with their light spectra, and optical and geometrical parameters. This report is a sequel to a Technical Monograph (Gausman et al., 1971) that presented research results on the spectral energy relations of leaves for 11 plant genera characterized by marked differences in leaf mesophyll arrangements. The research was based on the hypothesis that leaf mesophyll arrangements influence spectral energy relations of leaves and plant canopies.

Plants studied were corn (*Zea mays* L.), banana (*Musa acuminata* Colla (*M. cavendishii* Lamb.), begonia (*Begonia cucullata* Willd. (*B. semperflorens* Link & Otto), eucalyptus (*Eucalyptus camaldulensis* Dehnh. (*E. rostrata* Schlecht), rose (*Rosa* var. unknown), hyacinth (*Eichhornia crassipes* (Mart.) Solms, sedum (*Sedum spectabile* Boreau), ficus (*Ficus elastica* Roxb. ex Hornem.), oleander (*Nerium oleander* L.), ligustrum (*Ligustrum lucidum* Ait.), and crinum (*Crinum fimbriatulum* Baker).

Differences in leaf mesophylls among the 11 plant genera (Gausman et al., 1971) were compared with: (1) spectrophotometrically measured reflectance and transmittance and calculated absorptance values of the leaves over the 500- to 2500-nanometer (nm)[1] wavelength interval (WLI), (2) percent leaf water (H_2O) contents (oven-dry weight basis), (3) leaf thickness measurements, and (4) optical and geometrical leaf parameters.

Percent leaf H_2O contents of the 11 plant genera ranged from 60% for isolateral[2] (palisade layers on both sides) eucalyptus to 95% for succulent sedum and begonia leaves with storage cells on each side of a central chlorenchyma.

Dorsiventral rose and compact corn leaves (no palisade cells) were thinnest (about 0.15 mm), and succulent sedum leaves were thickest (about 0.82 mm).

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[1] Both nanometer (nm) and micrometer (μm) are used herein to denote spectral wavelengths. A nm is 10^{-3} μm; a nm is comparable to a millimicron (mμ). and a μm is equivalent to a micron (μ).

[2] Botanical terms are defined in the GLOSSARY OF TERMS, pages 80-81.

Spectral data for top (adaxial) and bottom (abaxial) leaf surfaces of all genera for 550-, 800-, 1000-, 1450-, 1650-, 1950-, and 2200-nm wavelengths (WL) were appended. Spectra of top leaf surfaces of oleander, corn, hyacinth, and eucalyptus were portrayed. At the 1000-nm WL, diffuse reflectance was highest for dorsiventral oleander and lowest for compact corn leaves; transmittance was lowest for oleander and highest for corn leaves; and absorptance for corn and oleander leaves was approximately 3 and 9%, respectively. The compact corn leaf with low light reflectance and high transmittance has fewer intercellular air spaces than the dorsiventral oleander leaf.

Because the interaction of plant genera with WL was small, mean spectral measurements of 550-, 800-, 1000-, 1450-, 1650-, 1950-, and 2200-nm WL were compared. Bottom leaf surfaces of dorsiventral leaves had higher reflectance values than top leaf surfaces, indicating that the spongy parenchyma contribute more to light scattering than the palisade parenchyma of the leaf mesophyll. This was substantiated by equal reflectance values of top and bottom surfaces of compact corn leaves.

Thick leaves of oleander, crinum, ficus, sedum, and ligustrum had the lowest percent transmittance. Mean spectrophotometrically measured transmittance values for the above wavelengths were lowest when light was passed from the top through the leaves compared with passing light from the bottom through the leaves. The difference in transmittance was caused by greater light diffusion by top leaf surfaces, since the spectrophotometer used irradiates the specimen with direct light.

Diffuse reflectance data were made absolute by correcting for decay of the MgO standard on the spectrophotometer, and absorptance was calculated as: 100 - [percent reflectance + percent transmittance]. When data for WL were averaged, highest absorptance values of 60.6, 58.2, 59.1, and 58.3% were obtained for the thick, dorsiventral ficus, crinum,, ligustrum, and oleander leaves, respectively; and lowest values of 40.4 and 39.0% were obtained for the thin, compact corn and thin, dorsiventral rose leaves, respectively.

Intensive study was given to the 550- and 1000-nm WL representing the visible (400 to 750 nm) and near-infrared (750 to 1450 nm) regions, respectively. At the 550-nm WL, reflectance was greater from the bottom than from the top of dorsiventral leaves, indicating that the chloroplasts in the palisade cells absorbed light. Bottom and top reflectance values were the same for the compact corn leaves. Considering top leaf surfaces only, thick, succulent sedum and thick ficus leaves had the highest and lowest reflectance values of 20 and 8%, respectively.

Percent transmittance was lowest for ficus and highest for succulent begonia leaves. Compact leaves of corn and succulent leaves of sedum and begonia with essentially a continuous mesophyll arrangement had the lowest light absorptance of approximately 70%. Thick dorsiventral leaves of ficus, oleander, and ligustrum with multiseriate epidermal layers or multipalisade layers had the highest light absorptance of 80 to 90%.

At the 1000-nm WL, reflectance values from top and bottom leaf surface measurements were essentially alike. Compact corn leaves had the lowest reflectance of 43% and succulent sedum and dorsiventral ficus, oleander, ligustrum, and crinum leaves had the highest reflectance of 53%. The 35.0% transmittance of oleander leaves was lowest, and 54.5% for corn was highest. The thin corn and rose leaves had the lowest absorptance values of 2 to 3% and the thick leaves of ligustrum, ficus, crinum, sedum, and oleander had the highest values of 8 to 11%.

Correlation coefficients were considered that accounted for at least 60% of the variation (r^2 x 100) between leaf thickness and reflectance; leaf thickness and absorptance; leaf H_2O content and reflectance; and leaf H_2O content and absorptance. Oleander, eucalyptus, and hyacinth leaves gave the highest coefficients among the plant genera studied. In general, negative coefficients were obtained between H_2O content and reflectance and between thickness and reflectance measurements; and, with the main exception of eucalyptus, positive coefficients were obtained between leaf H_2O content and absorptance and between thickness and absorptance calculations at 1450-, 1650-, 1950-, and 2200-nm WL.

Experimental values of leaf reflectance and transmittance for the 11 genera were transformed into effective optical constants. Such optical constants are useful in the prediction of reflectance phenomena associated with leaves either stacked in a spectrophotometer or arranged naturally in a plant canopy. The index of refraction n was plotted against WL to obtain disperion curves. The absorption coefficient k was shown to be equivalent to values determined previously for leaves from agricultural crops.

Each of the 11 genera has been analyzed to obtain geometrical parameters that specify the amount of H_2O and air in the leaf. The H_2O parameter is the thickness of liquid H_2O necessary to produce the observed leaf absorption. Observed and computed values of leaf H_2O thickness were obtained. Agreement was good except for the cases of ligustrum, crinum, and sedum. The air parameter is the number of identical compact layers into which the equivalent H_2O must be subdivided in order to achieve the observed partition of light between reflectance and transmittance.

A third parameter, infinite reflectance, is observed when leaves are piled sufficiently deep. Infinite reflectance was tabulated at 1.65 μm for all 11 genera. Infinite reflectance was shown to be a function of the calculated thickness of the identical compact layers of which a leaf is assumed to be composed.

The literature dealing with the interaction of light with plant leaves and leaf mesophyll structure is reviewed in the Technical Monograph (Gausman et al., 1971) and is not repeated here. Attention is directed, however, to the research of Aboukhaled (1966) who related the optical properties of leaves to their energy-balance, photosynthesis, and water use efficiency.

MATERIALS AND METHODS

Twenty plant genera were selected that are presently economically important or have the potential of becoming valuable in the Texas Lower Rio Grande Valley's agricultural enterprise. Pigweed was included because it is used by some farmers as a plow-under or green manure crop. Hence, it will be considered here as a crop rather than a weed. The leaves of the selected genera varied in their leaf mesophyll arrangements, leaf thicknesses and H_2O contents, and other structural differences such as palisade layer arrangement. Leaf characteristics of the 20 crops and the families they represent are indicated in Table 1, and typical photomicrographs of leaf transections are depicted in Fig. 1.

All plants were field grown in the summer of 1970 except that lettuce and onions were purchased in a fresh condition at a local market, soybeans and beans were grown in a greenhouse, and wheat was grown during the 1969 season.

Ten mature and healthy-appearing leaves were sampled from each of the 20 plant genus. Immediately after excision, leaves were wrapped in Saran or Glad-Wrap[3] to minimize dehydration. Leaves were wiped with a slightly dampened cloth preceding spectrophotometric measurements to remove surface contaminants. Only one-half (split longitudinally) of the tubular onion leaf was used for spectrophotometric measurements.

A Beckman Model DK-2A spectrophotometer equipped with a reflectance attachment was used to measure spectral diffuse reflectance and transmittance on adaxial[4] (top) surfaces of single leaves over the 500- to 2500-nm wavelength interval (WLI). Data have been corrected for decay of the MgO standard (Sanders and Middleton, 1953) to give absolute radiometric data. Absorptance was calculated from the absolute values as:
Absorptance = 100 - (percent reflectance + percent transmittance).

Leaf thickness and diffuse reflectance and transmittance measurements and tissue fixation processing were completed within 6 hours after leaves were harvested or obtained for each genera.

Leaf thickness was measured with a linear displacement transducer and digital voltmeter (Heilman et al., 1968). Leaf area was determined with a planimeter, with the exceptions that areas per leaf of corn, sorghum, and sugarcane were calculated by the method of Slickter, Wearden, and Pauli (1961); area per leaf of cotton was calculated by Johnson's method (1967). Percent leaf H_2O content was determined on an oven-dry weight basis by drying at 68°C for 72 hours and cooling in a desiccator before final weighing. Leaf thickness and H_2O content determinations were not made on wheat leaves.

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3 Trade and company names are for the convenience of the reader and do not imply endorsement or preferential treatment by the U. S. Department of Agriculture.

4 For simplicity, "top" will be used to denote adaxial leaf surfaces.

Table 1. Common, scientific, and family names, leaf mesophyll arrangements, and structural characteristics of plant leaves used in this study. Common names are used in the text.

Common name[5]	Scientific name[6]	Family name	Mesophyll arrangement[7]	Additional structural characteristics[8]
Avocado	*Persea americana* Mill.	*Lauraceae*	Dorsiventral	Thick cuticle, multiple palisade layers, long and narrow palisade cells.
Bean	*Phaseolus vulgaris* L.	*Leguminosae*	Dorsiventral	Very porous mesophyll
Cantaloupe	*Cucumis melo* L. var. *cantalupensis* Naud.	*Cucurbitaceae*	Dorsiventral	Multiple palisade layers, hairs lower epidermis.
Corn	*Zea mays* L.	*Gramineae*	Compact	Bulliform cells, hairs upper epidermis
Cotton	*Gossypium hirsutum* L.	*Malvaceae*	Dorsiventral	Glandular hairs, nectaries, lysigenous glands.
Lettuce	*Lactuca sativa* L.	*Compositae*	Compact	Large cells, porous mesophyll.
Okra	*Hibiscus esculentus* L.	*Malvaceae*	Dorsiventral	Well differentiated, porous mesophyll.
Onion	*Allium cepa* L.	*Amaryllidaceae*	Dorsiventral	Tubular leaves.
Orange	*Citrus sinensis* (L.) Osbeck	*Rutaceae*	Dorsiventral	Thick cuticle with wax layers, multiple palisade layers, lysigenous cavities.
Peach	*Prunus persica* (L.) Batsch	*Rosaceae*	Dorsiventral	Multiple palisade layers, porous mesophyll
Pepper	*Capsicum annuum* L. and other spp.	*Solanaceae*	Dorsiventral	Druse crystals
Pigweed	*Amaranthus retroflexus* L.	*Amaranthaceae*	Compact	Druse crystals, veins surrounded by large, cubical, parenchymatous cells

Table 1. (Continued)

Common name[5]	Scientific name[6]	Family name	Mesophyll arrangement[7]	Additional structural characteristics[8]
Pumpkin	Cucurbita pepo L.	Cucurbitaceae	Dorsiventral	Multiple palisade layers, hairs upper, and lower epidermis
Sorghum	Sorghum bicolor (L.) Moench	Gramineae	Compact	Bulliform cells
Soybean	Glycine max (L.) Merr.	Leguminosae	Dorsiventral	Porous mesophyll
Sugarcane	Saccharum officinarum L.	Gramineae	Compact	Bulliform cells
Sunflower	Helianthus annuus L.	Compositae	Isolateral	Hairs upper and lower epidermis
Tomato	Lycopersicon esculentum Mill.	Solanaceae	Dorsiventral	Hairs upper and lower epidermis, glandular hairs lower surface
Watermelon	Citrullus lanatus (Thunb.) Mansf.	Cucurbitaceae	Dorsiventral	Multiple palisade layers, glandular hairs lower surface
Wheat	Triticum aestivum L.	Gramineae	Compact	Bulliform cells

5 Generic names used as common names are not italicized or capitalized in the text.

6 Names are those used by New Crops Research Branch (Dr. Edward E. Terrell), ARS, USDA, Beltsville, Maryland.

7 Arbitrary definitions of mesophyll arrangements used herein are: dorsiventral, a usually porous (many intercellular air spaces) mesophyll with palisade parenchyma cells in its upper and spongy parenchyma cells in its lower part; compact mesophyll with little intercellular air space and no differentiation into palisade and spongy parenchyma cells; isolateral, tending to have long narrow cells throughout a porous mesophyll.

8 Definitions are given in the GLOSSARY OF TERMS, pages 80-81. References used were Esau (1965), Fahn (1967), Hayward (1938), and Metcalfe and Chalk (1957).

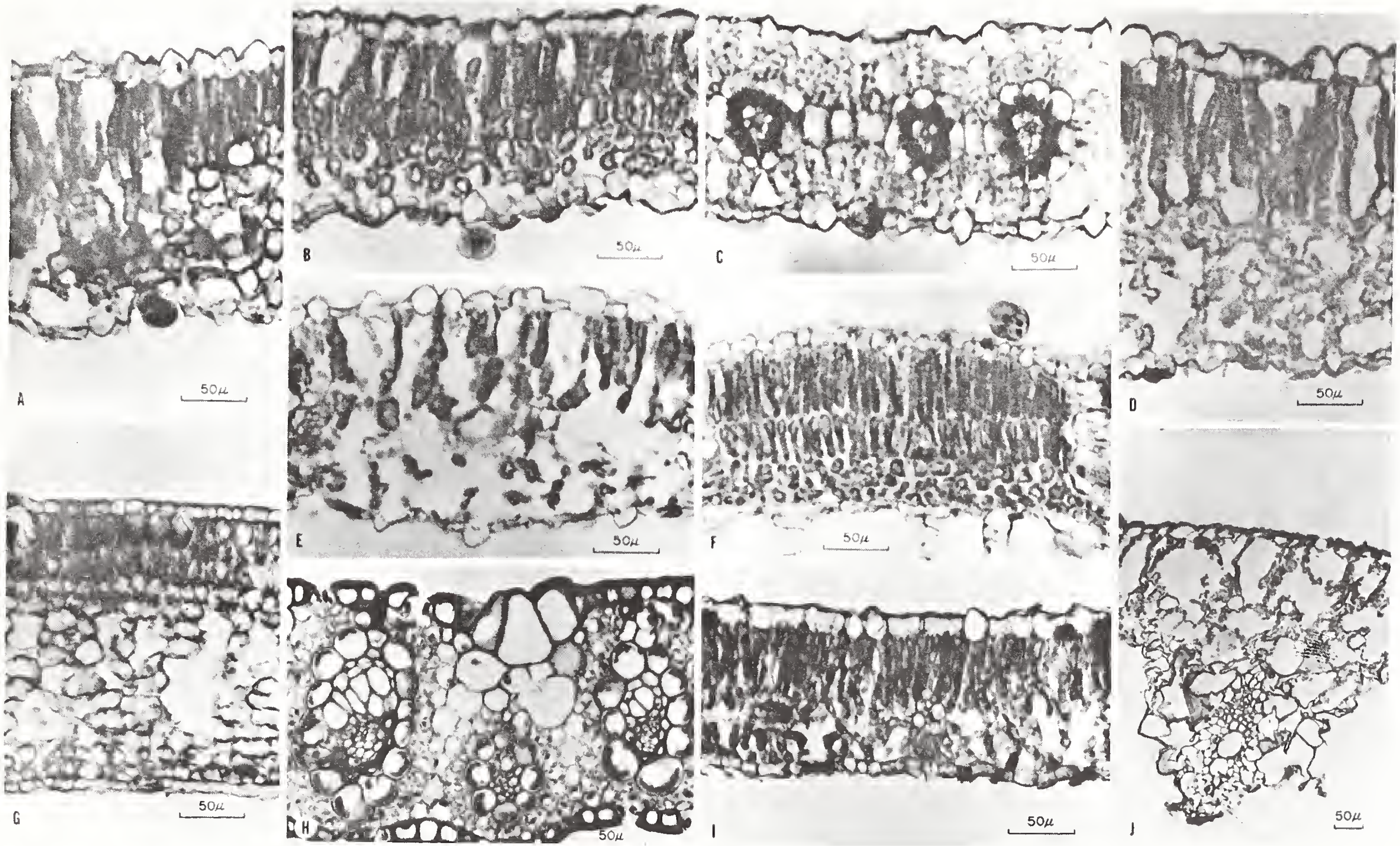
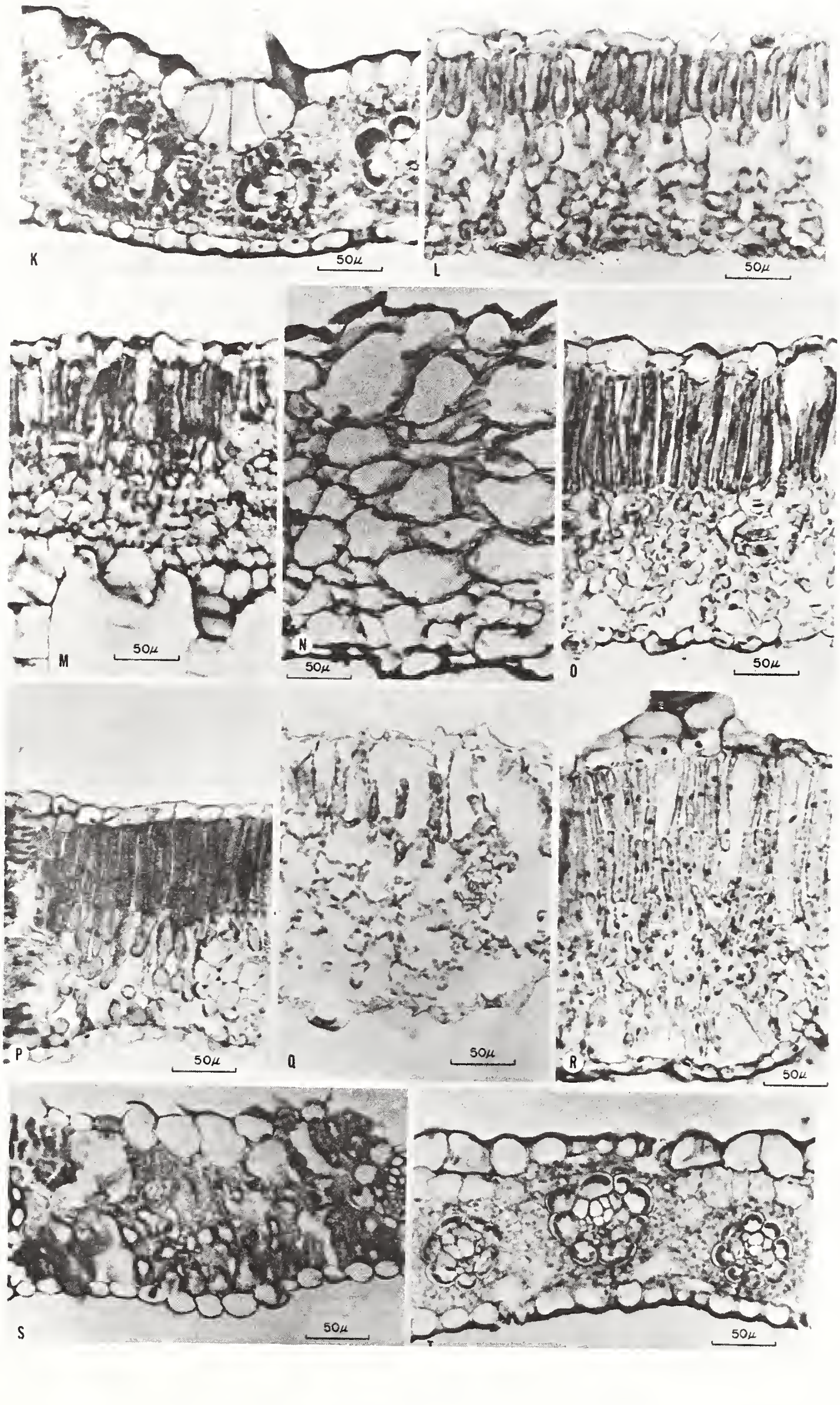


Fig. 1. Photomicrographs of leaf transections of 20 plant genera differing in leaf thicknesses, mesophyll arrangements, and other gross structural characteristics. All photomicrographs are 200 X except that onion is 80 X. A = cotton, B = watermelon, C = pigweed, D = tomato, E = soybean, F = pumpkin, G = orange, H = sugarcane, I = peach, J = onion, K = corn, L = pepper, M = cantaloupe, N = lettuce, O = okra, P = avocado, Q = bean, R = sunflower, S = wheat, T = sorghum.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Tissue pieces, taken near the center of leaves approximately one-half inch on either side of the midrib, were fixed in formalin-acetic acid-alcohol (FAA), dehydrated with a tertiary butanol series, embedded in paraffin, stained with either the safranin-fast green or the safranin-fast green-orange G combinations (Jensen, 1962), and transversally microtomed at 12 or 14 μ thicknesses. The relatively thick transverse sections were used to accentuate intercellular spaces, and thus enhance differences in mesophyll arrangements among the crops. Photomicrographs were obtained with a Zeiss Standard Universal Photomicroscope.

Spectrophotometrically measured reflectance and transmittance, and calculated absorptance of seven WL (550, 800, 1000, 1450, 1650, 1950, and 2200 nm) were analyzed for variance (Steel and Torrie, 1960); Duncan's Multiple Range Test (Duncan, 1955) was used to test differences among means of the seven WL at the 5% probability level. Standard deviation was calculated to compare the leaf reflectance, transmittance, and absorptance of the crops at the 550- and 1000-nm WL. Coefficients were calculated to evaluate the correlation of leaf thickness with leaf H_2O content. Coefficients were also obtained for correlations of reflectance, transmittance, and absorptance with g of H_2O/cm^3 of leaf tissue, leaf H_2O content on an oven-dry weight basis, and leaf thickness. Correlation coefficients of ± 0.775 were chosen as levels of significance because they account for 60% of the variation (r^2 x 100) between two series of variates. This is often referred to as the biological level of significance.

RESULTS AND DISCUSSION

Introduction

Mature leaves were used because leaf age affects spectral energy relations, leaf H_2O contents, and leaf thicknesses (Gausman et al., 1970).

The influence of leaf maturation on reflectance and transmittance is associated with compactness of internal cellular structure. Differences in cellular compactness of cotton leaves, sampled from fourth or fifth nodes down from plant apexes, affected reflectance of near-infrared light over the 750- to 1350-nm WLI (Gausman et al., 1969a, 1969b). Reflectance of older leaves was increased because of an increase in intercellular air spaces. Scattering of light within leaves occurs most frequently at cell wall (hydrated cellulose)-air cavity interfaces that have refractive indices of 1.4 and 1.0, respectively (Willstätter and Stoll, 1918; Weber and Olson, 1967).

Very immature cells in young leaves are primarily protoplasmic with little vacuolate cell sap storage (Esau, 1965; Fahn, 1967; Lundegårdh, 1966). During cell growth (extension), cell H_2O-filled vacuoles develop that usually coalesce to form a central sap cavity, and the protoplasm covers the cell wall in a thin layer. Hydrated leaves, compared with dehydrated leaves, reflected less and absorbed more light over the 500- to 2500-nm WLI (Allen and Richardson, 1968).

To facilitate interpretation, the 500- to 2500-nm WLI has been subdivided into three intervals (modified after Thomas, Wiegand, and Myers, 1967): (1) the visible light absorptance region 500 to 750 nm, dominated by pigments (primarily chlorophylls a and b, carotene, and xanthophylls); (2) the near-infrared region 750 to 1350 nm, a region of high reflectance and low absorptance considerably affected by internal leaf structure; and (3) the 1350- to 2500-nm WLI, a region influenced to some degree by leaf structure, but greatly affected by the amount of H_2O in the tissue--strong H_2O absorption bands occur at 1450 and 1950 nm.

Leaf Water and Thickness

Figure 2 depicts the leaf H_2O contents of 19 crops (wheat not included) on a dry weight basis. Thick, succulent lettuce leaves had the significantly highest H_2O content of 97.0%; the significantly lowest H_2O content occurred with avocado, orange, peach, and sugarcane leaves (60.6 to 72.4%) that as a group were statistically alike (Duncan's Test). Okra, soybean, pigweed, cotton, and watermelon leaves had essentially the same H_2O contents, 80.6 to 82.4%. Four other groups with similar H_2O contents within each group were corn and sorghum; sunflower and pumpkin; pepper and cantaloupe; and bean and onion. In some cases, results show no apparent association of leaf mesophyll arrangement with leaf H_2O content. For example, dorsiventral leaves had both high (bean and onion) and low (avocado and orange) leaf H_2O contents. However, compact corn, sorghum, and sugarcane leaves within the family Gramineae and dorsiventral cotton and okra leaves within the family Malvaceae had quite similar H_2O contents.

Figure 3 portrays leaf thicknesses of 19 crops (wheat not included). Sunflower, cantaloupe, lettuce, and onion leaves were thickest (.407 to .978 mm), and soybean, peach, pumpkin, and pigweed leaves were thinnest (.140 to .170 mm) compared with the other crop leaves. Other groups with statistically alike leaf thicknesses were: pigweed, okra, corn, pepper (.170 to .203 mm); okra, corn, pepper, cotton, watermelon (.198 to .232 mm); watermelon, orange, sugarcane, avocado, tomato, and bean (.232 to .263 mm); and orange, sugarcane, avocado, tomato, bean, and sorghum (.245 to .274 mm). Within the families Malvaceae and Gramineae, cotton and okra, and sugarcane and sorghum, respectively, were alike in leaf thickness.

Correlations of leaf thicknesses with H_2O contents of 19 crops were tested (wheat not included). Highest coefficients obtained were 0.58, 0.58, 0.57, and 0.56 for avocado, orange, tomato, and sorghum leaves, respectively, accounting for only 31 to 34% ($r^2 \times 100$) of the variation between leaf thicknesses and leaf H_2O contents. Remaining coefficients with respective crops were: peach, -.51; lettuce, .50; bean, .50; cotton, .48; watermelon, .45; corn, .43; soybean, .42; pepper, .41; pigweed, .40; sugarcane, .36; sunflower, .30; cantaloupe, .29; pumpkin, .26; okra, .05; and onion, .03. Thus leaf thickness and H_2O content of leaves are poorly correlated. There is no reason, however, why leaf thickness should be correlated with H_2O content unless the ratio of H_2O storage cells to non-H_2O storage cells changes. This could feasibly occur in succulent leaves.

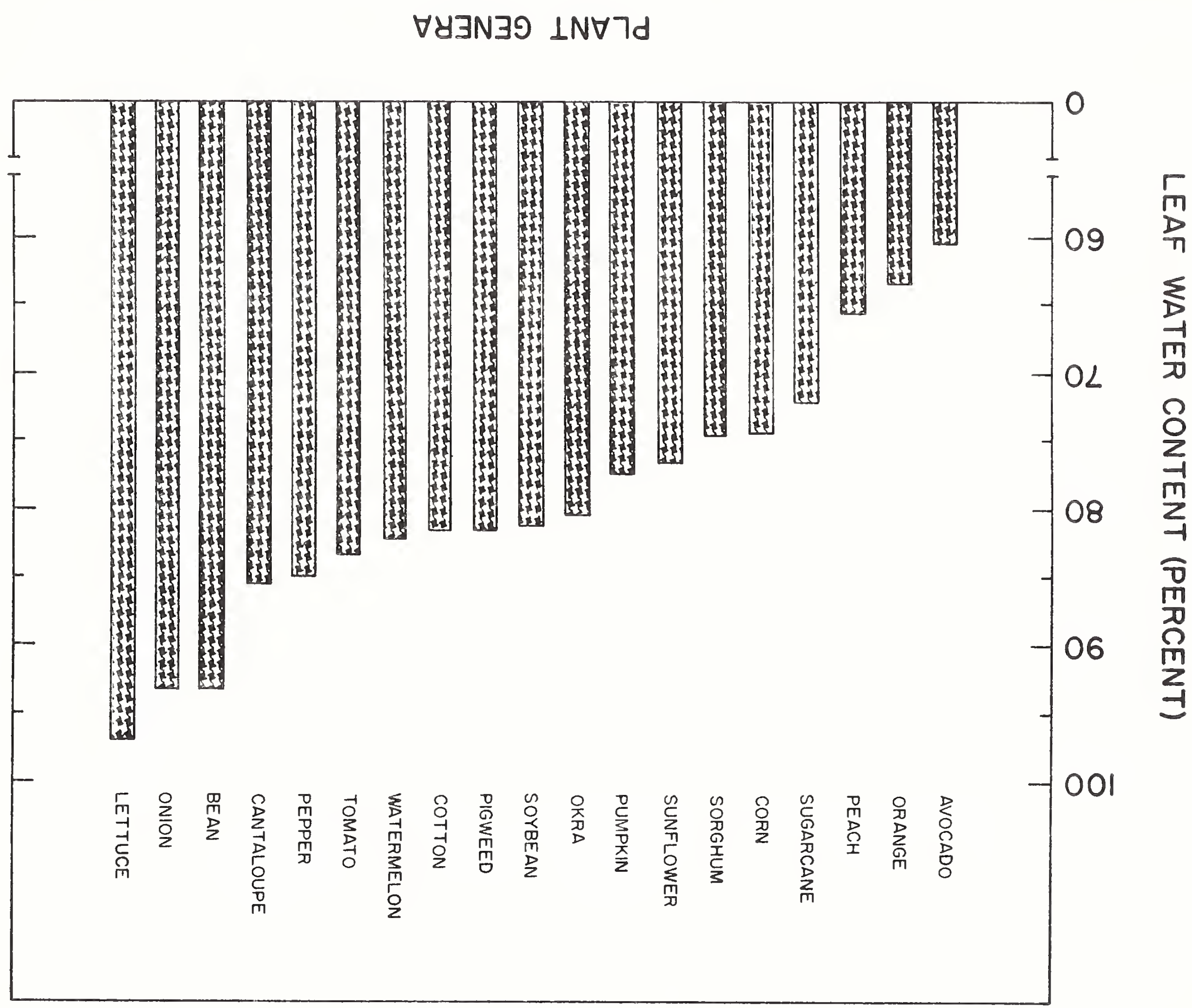


Fig. 2. Percent leaf H_2O contents on an oven-dry weight basis of 19 crops, wheat excluded, arranged in ascending order of H_2O contents.

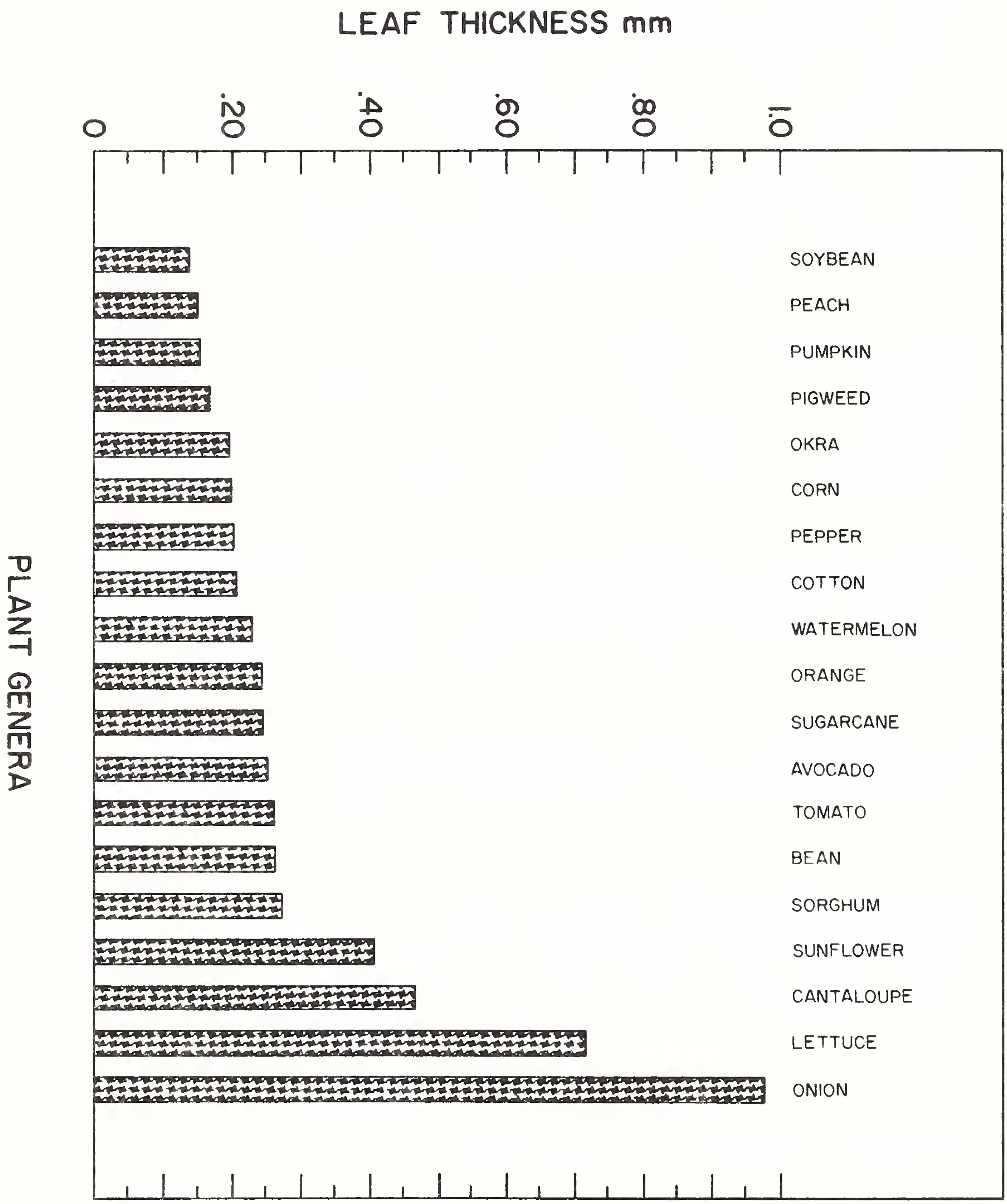


Fig. 3. Leaf thicknesses of 19 crops, wheat excluded, arranged in ascending order of thickness.

Spectrophotometric Measurements for Seven Selected Wavelengths (WL)

To reduce the enormous amount of spectrophotometrically generated data and facilitate interpretation, seven WL were selected from the 41 WL measured at 50-nm increments over the 500- to 2500-nm WLI. Data for reflectance, transmittance, and absorptance (representing means of 10 replications of each of 20 crops) for the 41 WL are given in Appendix Tables 1, 2, and 3. Reflectance, transmittance, and absorptance spectra for the 20 crops are portrayed in Appendix Figs. 1, 2, ..., 20. (See Appendix Figure Index, page 50.) Wavelengths selected were 550, 800, 1000, 1450, 1650, 1950, and 2200 nm; representing the visible region, beginning of the near-infrared plateau, a WL on the near-infrared plateau, 1450-nm H_2O absorption band, the 1650-nm peak following the 1450-nm H_2O absorption band, 1950-nm H_2O absorption band, and the 2200-nm peak following the 1950-nm H_2O absorption band, respectively.

The means of the seven WL will be briefly discussed (Table 2) followed by an introduction to leaf spectra over the 500- to 2500-nm WLI (Figs. 4 and 5) using the complementary 550- and 1000-nm WL data (Tables 3 and 4, respectively). The 550-nm WL data will be used to assess relative differences in chlorophyll concentrations of the crop leaves, and the 1000-nm WL data will be used to evaluate the influence of leaf mesophyll arrangements on light reflectance.

Table 2 presents the means of the selected seven WL for the reflectance, transmittance, and absorptance by leaves of the 20 crops. Considering reflectance, onion and bean leaves had the lowest (18.1%) and highest (31.6%) reflectance, respectively. Groups that had like but intermediate levels of reflectance were sunflower, pigweed, and cotton; pigweed, cotton, and tomato; cotton, tomato, sugarcane, and cantaloupe.

Statistically (Table 2), orange leaves had the lowest transmittance (20.4%), and soybean leaves had the highest transmittance (34.9%). Three groups, each alike in transmittance, were wheat, cantaloupe, sunflower, and avocado (25.6 to 26.3%); pepper, sugarcane, watermelon, and okra (27.1 to 27.9%); and corn, peach, and pumpkin (30.0 to 30.6%).

Among the 20 crops, onion leaves had the significantly highest absorptance (Table 2) of 57.4%, and sorghum and soybean leaves as a group had the lowest absorptance (36.7 to 36.9%). Other groups of crops that had like absorptances were: pumpkin, corn, and pigweed; corn, pigweed, pepper, and wheat; pepper, wheat, and okra; okra, bean, and cotton; bean, cotton, and watermelon; and watermelon, avocado, and sugarcane.

Leaf Spectra of Four Selected Crops

For illustrative and comparative purposes, the reflectance and transmittance spectra (500- to 2500-nm) of four selected crops (bean, avocado, sorghum, pigweed) are portrayed in Figs. 4 and 5.

Table 2. Average percent reflectance, transmittance, and absorptance of seven WL (550, 800, 1000, 1450, 1650, 1950, and 2200 nm) for each of 20 crops. Each average is based on 10 replications at each WL.

Crop	Reflectance[a/]	Crop	Transmittance[a/]	Crop	Absorptance[a/]
Onion	18.1 a	Orange	20.4 a	Sorghum	36.7 a
Lettuce	20.6 b	Bean	22.9 b	Soybean	36.9 a
Sunflower	24.8 c	Tomato	23.0 b	Peach	39.7 b
Pigweed	24.9 cd	Onion	24.5 c	Pumpkin	42.9 c
Cotton	25.3 cde	Wheat	25.6 d	Corn	43.6 cd
Tomato	25.4 de	Cantaloupe	25.7 d	Pigweed	43.7 cd
Sugarcane	25.5 e	Sunflower	26.1 d	Pepper	44.1 de
Cantaloupe	25.5 e	Avocado	26.3 de	Wheat	44.5 de
Watermelon	26.2 f	Pepper	27.1 ef	Okra	44.8 ef
Corn	26.4 f	Sugarcane	27.3 f	Bean	45.5 fg
Pumpkin	26.5 f	Watermelon	27.4 f	Cotton	45.6 fg
Avocado	27.0 g	Okra	27.9 f	Watermelon	46.4 gh
Okra	27.3 g	Cotton	29.1 g	Avocado	46.6 h
Soybean	28.2 h	Lettuce	29.2 g	Sugarcane	47.1 h
Pepper	28.9 i	Corn	30.0 h	Orange	48.8 i
Peach	29.8 j	Peach	30.5 h	Cantaloupe	48.8 i
Wheat	29.9 j	Pumpkin	30.6 h	Sunflower	49.2 i
Sorghum	30.2 j	Pigweed	31.4 i	Lettuce	50.2 j
Orange	30.8 k	Sorghum	33.1 j	Tomato	51.6 k
Bean	31.6 l	Soybean	34.9 k	Onion	57.4 l

a/ Values within columns followed by the same letter do not differ significantly at the 5% level using Duncan's Multiple Range Test.

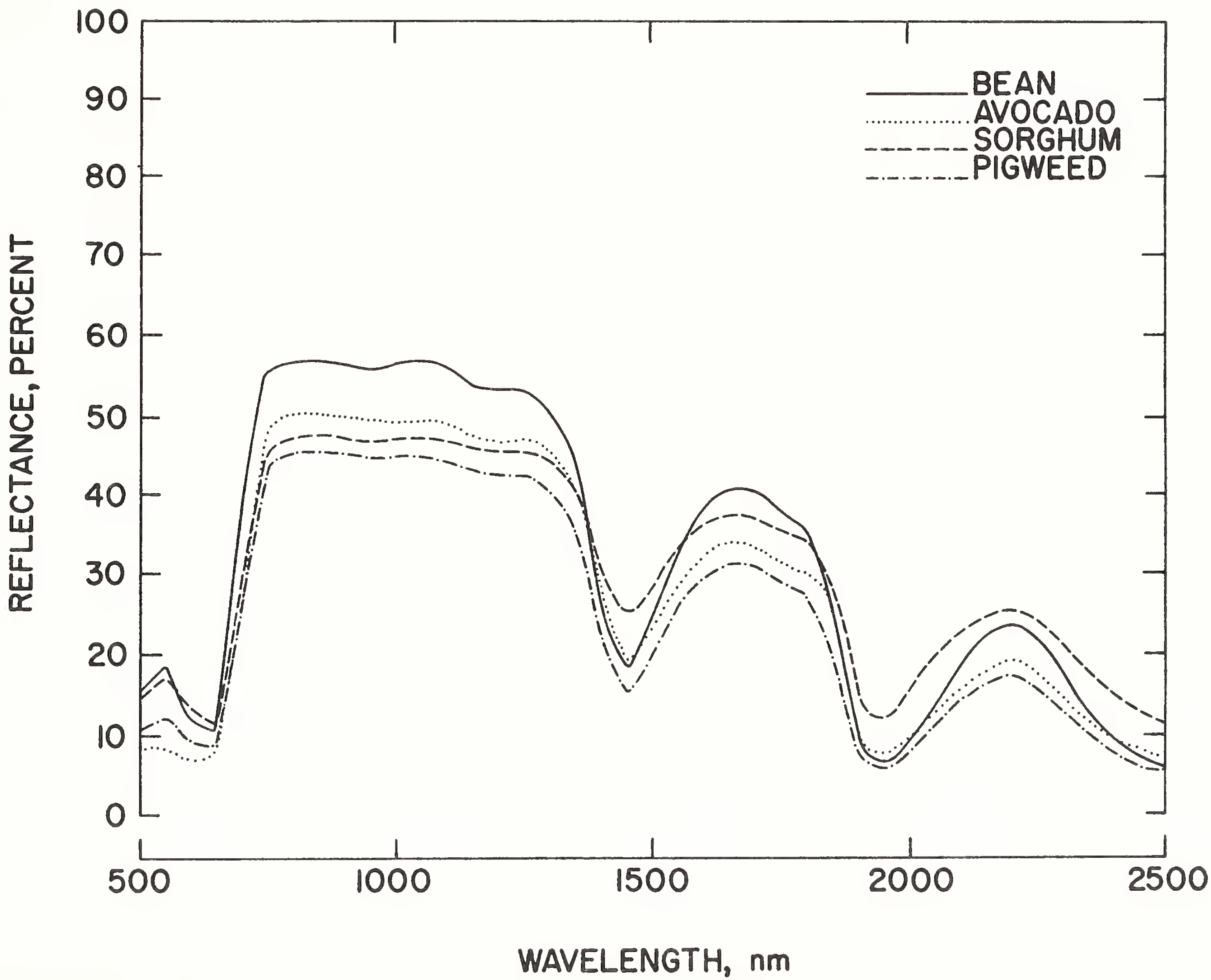


Fig. 4. Reflectance spectra of leaves of four crops. Pigweed and sorghum leaves have compact mesophylls; bean and avocado leaves have dorsiventral mesophylls.

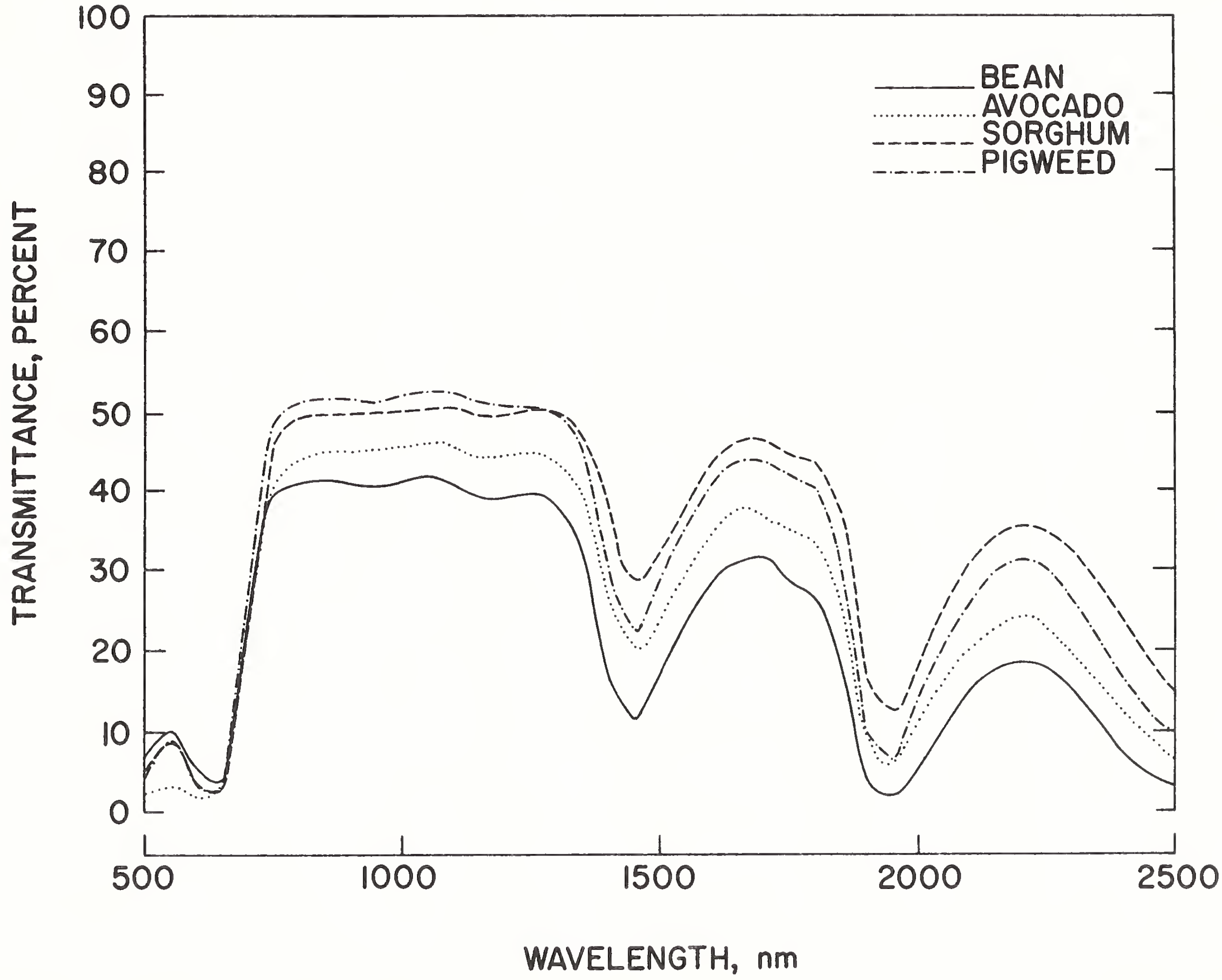


Fig. 5. Transmittance spectra of leaves of four crops. Pigweed and sorghum leaves have compact mesophylls; bean and avocado leaves have dorsiventral mesophyll.

Average percent reflectances (Fig. 4) at the 550-nm WL were 18.5, 12.4, 17.2, and 8.9% (Table 3) for bean, pigweed, sorghum, and avocado leaves, respectively. High reflectances are indicative of low concentrations of chlorophylls, and conversely low reflectances are indicative of high concentrations of chlorophylls.

At the 1000-nm WL, representing the 750- to 1350-nm near-infrared WLI, reflectances were 56.2, 49.7, 45.1, and 47.0% (Table 4) for bean, avocado, pigweed, and sorghum leaves, respectively. The dorsiventral bean and avocado leaves with porous mesophylls had higher reflectances than the relatively compact pigweed and sorghum leaves. This aspect will be discussed later.

Transmittance curves were similar in shape to the reflectance curves, Fig. 5, Tables 3 and 4. At the 550-nm WL, transmittances were 10.9, 9.5, 9.0, and 4.1% for bean, pigweed, sorghum, and avocado leaves, respectively. At the 1000-nm WL, transmittances were 42.0, 46.1, 52.4, and 50.3% for bean, avocado, pigweed, and sorghum leaves, respectively.

Calculated absorptances at the 550-nm WL were 70.6, 78.2, 73.8, and 87.0% (Table 3) for bean, pigweed, sorghum, and avocado leaves, respectively. In the near-infrared (1000-nm, Table 4) region, absorptances were 1.8, 2.5, 2.7, and 4.2% for bean, pigweed, sorghum, and avocado leaves, respectively.

Spectrophotometric Measurements at the 550-nm Wavelength (WL)

Intensive study was given to the 550- and 1000-nm WL, representing the visible (400 to 750 nm) and near-infrared (750 to 1350 nm) spectral regions, respectively. Tables 3 and 4 present light reflectance, transmittance, and absorptance values for the 550- and 1000-nm WL, respectively.

Mature, healthy leaves have approximately equal reflectance and transmittance. Lettuce leaves became suspect when it was noted that they had 35.3% reflectance and 53.7% transmittance at the 1000-nm WL (Table 4). Investigation revealed that fourth leaves in from the exterior of the lettuce heads were used. These leaves were not mature. It is characteristic of immature leaves to have a high light transmittance and low reflectance (Gausman et al., 1970). Therefore, means and their standard deviations for the data in Tables 3 and 4 were calculated omitting the data for lettuce leaves.

The mean reflectance of crop leaves at the 550-nm WL was 13.3% ± 2.8% (one standard deviation). All crops fell within the 13.3% ± 2.8% range except avocado and orange (8.9 and 10.2%, respectively), and corn, pepper, sorghum, bean, and sugarcane (16.2 to 18.6%).

The chlorophyll of green leaves usually absorbs 70 to 90% of the light in the blue (about 450 nm) or red part (about 675 nm) of the spectrum (Kleshnin and Shul'gin, 1959). Absorptance is smallest in the WL region around 550 nm, where a reflection peak of usually less than 20% occurs from top leaf surfaces. Avocado and orange leaves with a low reflectance at the 550-nm WL apparently had a much higher concentration of chlorophyll than corn, pepper, sorghum, bean, and sugarcane leaves with a high reflectance at the 550-nm WL. Low pigment content results often in higher reflectance (Carter and Myers, 1963; Myers, Ussery, and Rippert, 1963). Dr. J. R. Thomas, Weslaco, Texas (unpublished data) has shown that crops vary considerably in chlorophyll content. For example, sorghum and cantaloupe leaves ranged in chlorophyll concentration from 0.7 to 11.8 and 6.4 to 15.1 mg/g of plant tissue, respectively. Rabideau, French, and Holt (1946) found that light green leaves of cabbage and lettuce had 8 to 28% higher reflectance than the average of six darker green species. Thomas also showed a relation between pigment contents of leaves of some crops and their reflectance values.

Among transmittances in Table 3, orange, tomato, and avocado (1.9 to 5.5%) and okra, soybean, and onion (14.8 to 18.8%) fell outside of the 9.8% ± 4.2% range. In general, the spectral transmittance curves for all mature and healthy leaves are similar to their spectral reflectance curves over the 500- to 2500-nm WLI, but slightly lower in magnitude.

The differences among the crop leaves in the visible region are most apparent by considering the percent absorptance in Table 3. The mean absorptance for the crops is 76.9% ± 5.8%. All crops fell within the 76.9% ± 5.8% range except sugarcane, onion, bean, and pepper with low absorptances (69.2 to 70.6%) and peach, tomato, avocado, and orange with high absorptances (82.9 to 87.9%). The leaves with the high absorptances compared with the leaves with low absorptances have well-differentiated dorsiventral mesophylls with many chloroplasts in their dense, palisade parenchyma layers, Fig. 1. Aboukhaled (1966) has made preliminary analyses of the energy balance of single plant leaves from "low and high absorptivity" categories. He concluded that the optical properties of the leaves could be used to partition the total energy absorbed by the leaves into reradiation, convection, and transpiration.

Spectrophotometric Measurements at the 1000-nm WL

The 1000-nm WL (Table 4) can be used to evaluate the influence of leaf mesophyll arrangement on near-infrared (750 to 1350 nm) light reflectance. A leaf with a compact mesophyll has lower light reflectance and concomitantly higher transmittance than a leaf with a porous mesophyll (Gausman, Allen, and Cardenas, 1969). In Table 4, the mean reflectance of the crop leaves at the 1000-nm WL was 48.0% ± 3.9%. The reflectance of onion (38.5%) and orange and bean (55.6 and 56.2%, respectively) fell outside of the 48.0% ± 3.9% range. Only one-half of the tubular onion leaf was used for spectrophotometric measurements. Thus, discounting onion as an unusual leaf, compact pigweed, corn, sugarcane, and corn leaves (Fig. 1) had the lowest reflectances (45.1 to 46.0%), and dorsiventral leaves with very porous mesophylls such as bean, orange, and pepper had the highest reflectances (51.0 to 56.2%). An exception was the high reflectance of wheat leaves (51.2%), but examination of its photomicrograph in Fig. 1 indicates that its mesophyll is more porous than those of corn and sugarcane, even though they are all members of the family Gramineae, Table 1.

Table 3. Light reflectance, transmittance, and absorptance by leaves of 20 crops at the 550-nm WL. Crops are arranged in ascending order of their percent reflectance, transmittance, and absorptance.

Reflectance		Transmittance		Absorptance	
Crop	%	Crop	%	Crop	%
Avocado	8.9	Orange	1.9	Lettuce	25.4
Orange	10.2	Avocado	4.1	Sugarcane	69.2
Peach	10.9	Tomato	5.5	Onion	69.7
Tomato	11.0	Wheat	5.8	Bean	70.6
Sunflower	11.0	Peach	6.2	Pepper	70.6
Onion	11.6	Cantaloupe	8.7	Soybean	71.3
Pumpkin	11.8	Pumpkin	8.8	Okra	72.2
Cotton	11.8	Sorghum	9.0	Sorghum	73.8
Pigweed	12.4	Sunflower	9.1	Corn	74.0
Cantaloupe	12.7	Pigweed	9.5	Cotton	75.1
Okra	12.9	Watermelon	9.6	Watermelon	75.9
Soybean	13.1	Corn	9.8	Pigweed	78.2
Wheat	13.4	Bean	10.9	Cantaloupe	78.6
Watermelon	14.4	Sugarcane	12.2	Pumpkin	79.5
Corn	16.2	Pepper	12.6	Sunflower	79.9
Pepper	16.8	Cotton	13.1	Wheat	80.7
Sorghum	17.2	Okra	14.8	Peach	82.9
Bean	18.5	Soybean	15.6	Tomato	83.6
Sugarcane	18.6	Onion	18.8	Avocado	87.0
Lettuce	30.3	Lettuce	44.3	Orange	87.9
Mean a/	13.3		9.8		76.9
Standard deviation a/	2.8		4.2		5.8

a/ Lettuce was omitted because leaves were found to be immature.

Table 4. Light reflectance, transmittance, and absorptance of leaves of 20 crops at the 1000-nm WL. Crops are arranged in ascending order of their percent reflectance, transmittance, and absorptance.

Reflectance		Transmittance		Absorptance	
Crop	%	Crop	%	Crop	%
Lettuce	35.3	Orange	38.9	Soybean	1.8
Onion	38.5	Bean	42.0	Bean	1.8
Pigweed	45.1	Wheat	44.6	Pepper	2.4
Corn	45.7	Tomato	44.7	Pigweed	2.5
Sugarcane	45.7	Avocado	46.1	Sorghum	2.7
Soybean	46.0	Pepper	46.5	Peach	2.8
Cotton	46.6	Okra	47.3	Corn	3.2
Pumpkin	46.7	Sugarcane	47.6	Pumpkin	3.2
Watermelon	46.8	Watermelon	47.9	Cantaloupe	3.9
Sunflower	46.9	Peach	47.9	Cotton	4.0
Sorghum	47.0	Cantaloupe	48.8	Okra	4.0
Cantaloupe	47.3	Sunflower	49.1	Sunflower	4.1
Tomato	48.3	Cotton	49.4	Wheat	4.2
Okra	48.7	Pumpkin	50.1	Avocado	4.2
Peach	49.3	Sorghum	50.3	Watermelon	5.3
Avocado	49.7	Corn	51.2	Orange	5.5
Pepper	51.0	Soybean	52.2	Sugarcane	6.7
Wheat	51.2	Pigweed	52.4	Tomato	7.0
Orange	55.6	Lettuce	53.7	Onion	7.5
Bean	56.2	Onion	54.0	Lettuce	11.0
Mean a/	48.0		47.9		4.0
Standard deviation a/	3.9		3.7		1.7

a/ Lettuce was omitted because leaves were found to be immature.

The mean transmittance of all crop leaves (Table 4) was 47.9% ± 3.7%. All crops fell within this range except orange and bean (38.9 and 42.0%, respectively) and soybean, pigweed, and onion (52.2 to 54.0%). Omitting onion and lettuce leaves for reasons given previously, compact pigweed, sorghum, and pumpkin leaves had high transmittance and porous dorsiventral leaves had low transmittance. The main exceptions were dorsiventral soybean leaves with relatively high transmittance (52.2%) and compact wheat leaves with relatively low reflectance (44.6%).

Absorptance values are also given in Table 4; the mean of all crop leaves was 4.0% ± 1.7%. Soybean and bean leaves (1.8%) and sugarcane, tomato, and onion leaves (6.7 to 7.5%) fell outside the 4.0% ± 1.7% range. Soybean and bean leaves with the low absorptance of near-infrared light both have extremely porous mesophylls, Fig. 1. Although the literature indicates that thick leaves have higher absorptance than thin leaves (Rabideau et al., 1946; Moss and Loomis, 1952), coefficients for the correlation between absorptance and leaf thickness were low. This will be discussed in the next section.

Correlations among Spectrophotometric Measurements and Leaf H_2O Content and Thickness

To make a relative comparison among correlation coefficients, a level of $r = 0.775$ was chosen as the level of significance, because it accounts for 60% ($r^2 \times 100$) of the variation for the association between two series of variates. Wheat was not included in calculating correlation coefficients because leaf H_2O and thickness determinations were not made.

Coefficients were calculated, using the means of the 10 leaves of each crop, to test the correlation of leaf thickness, percent H_2O content, and g of H_2O/cm^3 of leaf tissue with reflectance at the 550-, 800-, 1000-, 1450-, 1650-, 1950-, and 2200-nm WL. Negative coefficients that exceeded -0.775 were obtained for the correlation between leaf thickness and reflectance at the 1450-, 1650-, and 2200-nm WL. There were no high positive correlation coefficients. Correlation coefficients for WL of 800, 1000, 1450, 1650, 1950, and 2200 nm were: 0.53, -0.42, -0.45, -0.65, -0.53, -0.60, and -0.52 for the relation between leaf H_2O content and reflectance; 0.30, -0.60, -0.65, -0.76, -0.85, -0.46, and -0.80 for the relation between leaf thickness and reflectance; and 0.07, -0.17, -0.18, -0.31, -0.28, -0.58, and -0.31 for the relation between g of H_2O/cm^3 of plant tissue, respectively.

The coefficients for correlations of leaf reflectance, transmittance, and absorptance with percent leaf H_2O content for the 10 leaves of each crop are shown in Table 5. Sugarcane, corn, pigweed, and tomato leaves had negative coefficients that exceeded -0.775 for the correlation between light reflectance and percent leaf H_2O content at 1450-, 1650-, and 2200-nm; 550- and 1450-nm; 1450-nm; and 1450- and 2200-nm WL, respectively. In general, largest coefficients were obtained at the 1450-nm H_2O absorption band, the 1650-nm peak following the 1450-nm H_2O absorption band, and the 2200-nm peak following the 1950-nm H_2O absorption band. As percent H_2O in the leaves increased, reflectance decreased over the 1350- to 2500-nm WLI. No coefficients exceeded ± 0.775 for correlations either of leaf transmittance or absorptance with percent leaf H_2O content.

Table 5. Coefficients for correlations of reflectance (R), transmittance (T), and absorptance (A) of light with percent leaf H_2O content at seven wavelengths (nm) of top leaf surfaces of 19 crops. Crops are in order of ascending H_2O content to correspond with Fig. 2. Wheat is not included.

Crop	Correlation coefficients[a/]											
	550 nm			800 nm			1000 nm			1450 nm		
	R	T	A	R	T	A	R	T	A	R	T	A
1. Avocado	-.14	.52	-.37	-.31	.30	.17	-.34	.21	.34	.43	.39	-.41
2. Orange	-.24	.67	-.31	-.45	.62	-.29	-.49	.61	-.22	-.25	.48	-.38
3. Peach	-.35	.58	-.15	-.55	.26	.15	-.52	.20	.19	.22	.38	-.35
4. Sugarcane	.15	.46	-.41	-.52	.54	-.14	-.56	.48	.00	-.<u>93</u>	-.43	.75
5. Corn	-.<u>98</u>	.02	.29	-.39	.41	.03	-.39	.38	.13	-.<u>78</u>	-.34	.59
6. Sorghum	-.52	-.22	.37	-.21	.18	.04	-.28	.06	.22	-.67	-.47	.72
7. Sunflower	.32	.48	-.50	-.22	-.05	.24	-.26	-.05	.26	-.73	-.34	.57
8. Pumpkin	.38	.10	-.39	-.18	-.25	.31	-.20	-.25	.35	-.25	-.59	.56
9. Okra	-.26	.40	-.17	-.24	.11	.15	-.30	.01	.28	-.69	-.41	.58
10. Soybean	.48	.14	-.52	.07	-.26	.33	.14	-.33	.39	-.44	-.31	.35
11. Pigweed	.05	.72	-.67	-.17	-.03	.19	-.23	-.11	.31	-.<u>80</u>	-.50	.68
12. Cotton	.28	-.00	-.08	.53	-.06	-.52	.54	-.00	-.57	.26	.01	-.11
13. Watermelon	.44	-.06	-.15	.30	-.28	.10	.33	-.30	.09	.19	-.27	.18
14. Tomato	.16	.39	-.35	-.18	.27	.02	-.30	.19	.19	-.<u>81</u>	-.16	.50
15. Pepper	-.05	-.43	.28	.44	-.58	.04	.40	-.58	.08	-.18	-.70	.62
16. Cantaloupe	-.12	.59	-.45	.12	.37	-.44	-.23	.20	-.04	-.74	-.46	.64
17. Bean	-.56	.27	.06	-.67	.42	-.09	-.55	.43	-.23	.34	.56	-.51
18. Onion	.24	.54	-.50	-.61	.49	.47	-.62	.57	-.20	-.58	-.02	.22
19. Lettuce	.54	.59	-.29	-.01	-.06	-.24	.08	.00	-.22	.22	.13	-.15

a/ Correlation coefficients underscored equal or exceed ± 0.775.

Table 5. Continued.

Crop	Correlation coefficients[a/]								
	1650 nm			1950 nm			2200 nm		
	R	T	A	R	T	A	R	T	A
1. Avocado	.52	.39	-.47	.51	.43	-.47	.61	.48	-.53
2. Orange	-.29	.60	-.44	-.06	.41	-.55	-.11	.59	-.54
3. Peach	.04	.35	-.32	.39	.42	-.43	.35	.50	-.49
4. Sugarcane	-.91	-.01	.61	-.80	-.67	.76	-.92	-.22	.58
5. Corn	-.72	-.01	.51	-.74	-.46	.59	-.75	-.21	.51
6. Sorghum	-.57	-.21	.55	-.59	-.58	.72	-.64	-.33	.61
7. Sunflower	-.59	-.21	.49	-.32	-.44	.49	-.55	-.21	.38
8. Pumpkin	-.20	-.44	.48	-.01	-.59	.57	-.15	-.48	.46
9. Okra	-.67	-.23	.51	-.56	-.51	.58	-.68	-.33	.52
10. Soybean	-.20	-.32	.39	-.27	-.30	.30	-.46	-.31	.35
11. Pigweed	-.68	-.31	.56	-.62	-.64	.71	-.70	-.36	.53
12. Cotton	.51	.07	-.30	-.17	.05	.05	.34	.11	-.21
13. Watermelon	.39	-.25	.09	.28	-.18	.10	.39	-.20	.07
14. Tomato	-.72	-.01	.45	-.56	-.31	.51	-.77	-.06	.39
15. Pepper	.26	-.66	.44	-.18	-.70	.65	-.03	-.67	.57
16. Cantaloupe	-.59	-.36	.54	-.54	-.48	.68	-.64	-.41	.54
17. Bean	.41	.54	-.55	.05	.49	-.37	.46	.56	-.56
18. Onion	-.65	.06	.25	-.34	-.29	.34	-.59	-.00	.19
19. Lettuce	.15	.10	-.11	.40	.22	-.56	.22	.13	-.12

The coefficients for correlations of light reflectance, transmittance, and absorptance with leaf thickness for the 10 leaves of each crop are given in Table 6. Considering the correlations of reflectance and transmittance with leaf thickness, soybean was the only crop that had positive coefficients exceeding 0.775 at the 550-, 800-, and 1000-nm WL, and a negative coefficient for transmittance exceeding -0.775 at the 1000-nm WL. The reason for this is unknown. It seems plausible, however, that leaf anatomy or cellular configuration is involved; Fig. 1 shows that a mature soybean leaf has a very porous mesophyll with few spongy parenchyma cells compared with the other crop leaves. Soybean leaves also had high negative coefficients for reflectance at the 1450-, 1950-, and 2200-nm WL and for transmittance at the 1450-, 1650-, 1950-, and 2200-nm WL. Peach, pigweed, tomato, bean, and onion crops also had high negative correlation coefficients for transmittance at two or more of the 1450-, 1650-, 1950-, and 2200-nm WL. These WL are within the H_2O absorption spectral range (1350- to 2500-nm WLI), and as leaf H_2O content increased, light reflectance and transmittance decreased and absorptance increased. High positive coefficients were obtained for the correlation between leaf thickness and percent light absorptance for the soybean, peach, pigweed, bean, and onion crops at three or more of the 1450-, 1650-, 1950-, and 2200-nm WL.

It was thought that the amount of H_2O in the leaf tissue that was placed over the port of the spectrophotometer might have influenced the spectral energy measurements. Accordingly, g of H_2O/cm^3 of leaf tissue was calculated for each crop leaf used in this study except for wheat. Coefficients for the correlations of g of H_2O/cm^3 of leaf tissue with reflectance, transmittance, and absorptance are given in Table 7. There was no correlation between reflectance and g of H_2O/cm^3 of leaf tissue. With transmittance, coefficients above 0.775 occurred with only okra leaves at 1000-, 1450-, 1650-, 1950-, and 2200-nm WL. The correlation between absorptance and g of H_2O/cm^3 of leaf tissue gave high positive coefficients for okra leaves at 1450-, 1650-, and 2200-nm. Variability in g of H_2O/cm^3 among okra leaves had an important influence on their light absorptance and transmittance compared with the variability among leaves of the other crops.

Optical and Geometrical Leaf Parameters

The flat-plate model (Allen et al., 1969) for calculation of effective optical constants of leaves has been applied to leaves of the 20 crops. All available values of reflectance and transmittance for the leaves of 20 crops were reduced to average values $\bar{a}$, $\bar{b}$ at the 41 WL 0.50, 0.55, ..., 2.50 µm. Optical parameters a, b are defined elsewhere (Allen and Richardson, 1968). Thirteen data points in the vicinity of plant pigment and H_2O absorption bands were deleted in advance (WL 0.50, 0.55, 0.60, 0.65, 0.70, 1.40, 1.45, 1.50, 1.90, 1.95, 2.00, 2.45, and 2.50 µm) from calculations of refractive indices, n. Such editing is justified because determination of the index of refraction n is weak in the vicinity of absorption bands.

Table 6. Coefficients for correlations of reflectance (R), transmittance (T), and absorptance (A) of light with leaf thicknesses at seven wavelengths (nm) of top leaf surfaces of 19 crops. Crops are in order of ascending leaf thickness to correspond with Fig. 3. Wheat is not included.

Crop	Correlation coefficients[a/]											
	550 nm			800 nm			1000 nm			1450 nm		
	R	T	A	R	T	A	R	T	A	R	T	A
1. Soybean	.78	-.65	-.03	.85	-.89	.31	.84	-.92	.52	-.80	-.93	.92
2. Peach	.45	-.40	.01	.54	-.29	-.12	.50	-.35	-.01	-.66	-.82	.83
3. Pumpkin	.30	-.26	-.19	-.06	-.33	.29	.02	-.27	.20	.04	-.10	.06
4. Pigweed	.61	.25	-.42	.64	-.35	-.17	.59	-.40	-.06	-.61	-.81	.83
5. Okra	.34	.03	-.23	.46	.22	-.67	.46	.17	-.61	-.08	-.07	.08
6. Corn	-.44	-.48	.58	.41	-.24	-.58	.42	-.28	-.50	-.40	-.75	.68
7. Pepper	.13	-.34	.13	.59	-.44	-.25	.56	-.48	-.18	-.41	-.57	.61
8. Cotton	-.39	-.25	.37	.38	-.22	-.07	.34	-.23	-.01	-.48	-.41	.50
9. Watermelon	-.23	-.68	.70	.40	-.57	.45	.34	-.53	.43	-.33	-.52	.55
10. Orange	-.24	-.47	.66	.12	-.68	.63	.15	-.69	.60	-.09	-.52	.63
11. Sugarcane	-.09	-.27	.24	.28	.17	-.46	.23	.14	-.40	-.54	-.26	.44
12. Avocado	-.08	-.62	.56	.56	-.56	-.26	.58	-.52	-.36	-.59	-.66	.66
13. Tomato	.28	-.34	.12	.54	-.44	-.37	.43	-.47	-.12	-.54	-.81	.82
14. Bean	.23	-.51	.27	-.35	-.61	.40	.16	-.63	.72	-.61	-.77	.77
15. Sorghum	-.54	-.24	.39	.01	.48	-.46	.00	.46	-.43	-.36	-.03	.22
16. Sunflower	.23	.18	-.22	.05	-.04	.01	-.02	-.04	.06	-.63	-.16	.40
17. Cantaloupe	.73	.05	-.33	.25	-.04	-.14	.23	-.19	.03	-.33	-.77	.68
18. Lettuce	.30	.08	-.17	-.00	.11	-.07	-.29	-.11	.29	-.43	-.42	.52
19. Onion	-.04	-.29	.20	.02	-.27	.38	-.07	.28	-.28	-.23	-.89	.90

a/ Correlation coefficients underscored equal or exceed ± 0.775.

Table 6. Continued.

Crop	Correlation coefficients[a/] 1650 nm			1950 nm			2200 nm		
	R	T	A	R	T	A	R	T	A
1. Soybean	.49	-.92	.89	-.78	-.93	.91	-.78	-.94	.93
2. Peach	-.27	-.73	.75	-.67	-.85	.83	-.60	-.82	.82
3. Pumpkin	.08	-.15	.08	.17	-.10	.04	.02	-.17	.14
4. Pigweed	-.09	-.66	.67	-.54	-.86	.86	-.52	-.80	.85
5. Okra	.17	.06	-.13	-.18	-.12	.16	-.05	-.05	.06
6. Corn	-.10	-.60	.58	-.41	-.76	.69	-.36	-.72	.68
7. Pepper	.19	-.55	.38	-.23	-.64	.62	-.25	-.59	.59
8. Cotton	-.19	-.31	.37	-.71	-.48	.65	-.48	-.34	.44
9. Watermelon	-.00	-.56	.60	-.33	-.53	.57	-.42	-.58	.64
10. Orange	-.01	-.65	.67	-.08	-.39	.67	-.13	-.59	.66
11. Sugarcane	-.33	-.10	.29	-.25	-.33	.33	-.46	-.19	.35
12. Avocado	-.49	-.67	.69	-.41	-.69	.66	-.68	-.69	.70
13. Tomato	-.23	-.69	.68	-.13	-.80	.59	-.50	-.73	.77
14. Bean	-.71	-.73	.79	-.52	-.81	.79	-.70	-.78	.80
15. Sorghum	-.26	.19	-.00	-.33	-.14	.26	-.38	.02	.17
16. Sunflower	-.58	-.11	.40	-.02	-.23	.21	-.57	-.14	.32
17. Cantaloupe	-.47	-.65	.72	.35	-.77	.31	-.46	-.76	.74
18. Lettuce	-.50	-.41	.52	-.41	-.40	.46	-.45	-.42	.51
19. Onion	-.37	-.86	.92	.05	.03	-.05	-.23	-.89	.92

Table 7. Coefficients for correlations of reflectance (R), transmittance (T), and absorptance (A) of light with g of H_2O/cm^3 of leaf tissue at seven wavelengths (nm) of top leaf surfaces of 19 crops. Crops are arranged in order of ascending g of H_2O/cm^3 of leaf tissue. Wheat is not included.

Crop	Correlation coefficients[a/]											
	550 nm			800 nm			1000 nm			1450 nm		
	R	T	A	R	T	A	R	T	A	R	T	A
1. Cotton	-.33	.24	-.14	-.32	.13	.15	-.31	.10	.17	-.41	-.09	.23
2. Pepper	-.31	-.17	.26	-.42	.12	.36	-.45	.14	.34	.11	.10	-.13
3. Corn	-.49	.25	-.07	-.53	.57	.04	-.53	.55	.10	-.53	-.02	.26
4. Tomato	-.08	.47	-.30	-.54	.33	.47	-.42	.41	.15	-.12	.42	-.23
5. Cantaloupe	-.63	-.02	.27	-.06	.22	-.17	-.25	.24	-.07	-.61	.02	.24
6. Pumpkin	.64	-.08	-.36	-.16	-.42	.42	-.19	-.44	.49	.03	-.60	.46
7. Sorghum	-.56	-.46	.54	-.03	.05	-.02	-.09	.03	.06	-.16	-.35	.34
8. Watermelon	.55	-.45	.14	.39	-.53	.39	.41	-.56	.41	-.05	-.64	.57
9. Soybean	-.37	.29	.04	-.32	.56	-.50	.25	.56	-.64	.53	.56	-.56
10. Bean	-.23	.15	.00	-.29	.26	-.14	-.15	.29	-.28	.35	.39	-.40
11. Orange	.19	-.18	-.05	-.08	-.43	.52	-.09	-.45	.55	-.20	-.49	.65
12. Sugarcane	.14	.40	-.36	-.34	.44	-.21	-.38	.40	-.08	-.69	-.31	.55
13. Sunflower	.55	.19	-.32	.12	-.27	.22	.10	-.30	.26	-.34	-.66	.62
14. Pigweed	.04	-.55	.48	.65	-.43	-.08	.62	-.39	-.08	.25	-.28	.11
15. Avocado	.11	-.16	.09	.19	-.14	-.17	.18	-.22	-.02	-.22	-.21	.22
16. Okra	-.29	-.40	.49	.31	-.73	.34	.26	-.<u>78</u>	.48	-.54	-.<u>86</u>	.<u>80</u>
17. Peach	-.49	.43	.06	-.53	.67	-.31	-.52	.70	-.36	.13	.59	-.46
18. Lettuce	.26	.24	-.25	-.22	-.31	.39	-.49	-.50	.69	-.57	-.66	.<u>78</u>
19. Onion	-.42	.19	-.06	-.22	.06	.35	-.23	.14	.01	-.36	.19	-.05

a/ Correlation coefficients underscored equal or exceed ± 0.775.

Table 7. Continued

Crop	Correlation coefficients[a/]								
	1650 nm			1950 nm			2200 nm		
	R	T	A	R	T	A	R	T	A
1. Cotton	-.44	-.07	.26	-.14	-.07	.11	-.39	-.10	.22
2. Pepper	-.21	.12	.02	-.08	.16	-.10	.05	.12	-.12
3. Corn	-.63	.27	.21	-.50	-.17	.30	-.59	.07	.23
4. Tomato	-.26	.41	-.16	-.26	.33	-.07	-.15	.40	-.22
5. Cantaloupe	-.39	-.00	.17	-.72	.16	.36	-.46	-.02	.19
6. Pumpkin	-.04	-.53	.48	.36	-.52	.37	.11	-.50	.38
7. Sorghum	-.17	-.19	.28	-.09	-.40	.36	-.14	-.32	.35
8. Watermelon	.28	-.59	.50	.17	-.59	.50	.10	-.60	.51
9. Soybean	-.01	.55	-.59	.43	.57	-.54	.46	.55	-.55
10. Bean	.45	.38	-.43	.22	.37	-.36	.47	.42	-.46
11. Orange	-.24	-.44	.60	.23	-.51	.52	-.21	-.48	.58
12. Sugarcane	-.63	.02	.40	-.62	-.48	.57	-.69	-.15	.42
13. Sunflower	-.22	-.61	.64	.07	-.64	.54	-.33	-.64	.62
14. Pigweed	.52	-.36	.15	.16	-.11	.04	.20	-.33	.22
15. Avocado	.05	-.19	.14	-.25	-.17	.20	-.06	-.15	.13
16. Okra	-.38	-.<u>86</u>	<u>.83</u>	-.28	-.<u>81</u>	.68	-.54	-.<u>85</u>	<u>.82</u>
17. Peach	-.06	.71	-.58	.44	.52	-.52	.27	.68	-.61
18. Lettuce	-.70	-.70	<u>.82</u>	-.45	-.22	.48	-.60	-.67	<u>.77</u>
19. Onion	-.25	.17	-.03	.07	-.24	-.07	-.29	.18	-.08

Figures 6a, 6b, ..., 6t display the 95% confidence bands of the dispersion curves. Computational and statistical procedures used have appeared elsewhere (Allen et al., 1970; Freeze, 1964). Statistically, 95% of experimental points fall within the confidence limits. The dispersion curves of Figs. 6a, 6b, ..., 6t assumed to be cubics in wavelength λ, are expressed by the relation

$$n = \Sigma\, a_i \lambda^i \quad , \tag{1}$$

where the coefficients a_0, ..., a_3 were determined by regression. Table 8 contains the coefficients of Eq. (1) for all data discussed.

The dispersion curves of most of the leaves illustrated in Fig. 6 are remarkably similar. With the exceptions of onion (H), pigweed (J), and lettuce (S), the dispersion curves are characterized by similar shapes and relatively close confidence bands. The exceptions mentioned are cases where the flat-plate model (Allen et al., 1969) appears not to apply. However, the onion, pigweed, and lettuce leaves indicated as exceptions were different from the other crop leaves--only one-half of the tubular onion leaves was used, lettuce leaves were immature, and veins of pigweed leaves (Fig. 1) are surrounded by large, cubical, parenchymatous cells.

Table 9 includes the leaf parameters that relate to the amount of water and air in the leaf. As explained previously (Allen et al., 1969, 1970a, 1970b) the quantity D in the flat-plate model is the equivalent thickness of pure liquid H_2O necessary to produce the observed leaf absorption. The quantity N in the model is the number of compact layers into which D must be subdivided in order to achieve the observed partition of energy between reflectance and transmittance. The infinite reflectance R_∞ at 1.65 μm (Allen and Richardson, 1968), produced by leaves piled sufficiently deep, is listed in column 5 of Table 9. The quantity R_∞ can be measured directly; the number listed in Table 9, however, is a calculated value obtained by techniques previously described (Allen and Richardson, 1968). The entries of Table 9 were obtained by adjusting the quantity D, over the spectral range 1.4 to 2.5 μm, to achieve the best fit of the leaf absorption k to the absorption k_o for pure liquid H_2O. Column 6 of Table 9 is the standard error (S.E.) calculated from the relation

$$S.E. = \{\Sigma[\log\,(k/k_o)]^2/[n(n-1)]\}^{\frac{1}{2}} \quad . \tag{2}$$

The summation in Eq. (2) includes the 23 values at 0.05 μm intervals over the range 1.4 to 2.5 μm. This quantity S.E. (standard error) can be considered a figure of merit because S.E. would vanish entirely if the model was exact and the material was H_2O. The quantities D and S.E. in Table 9 are positively correlated (r = 0.728).

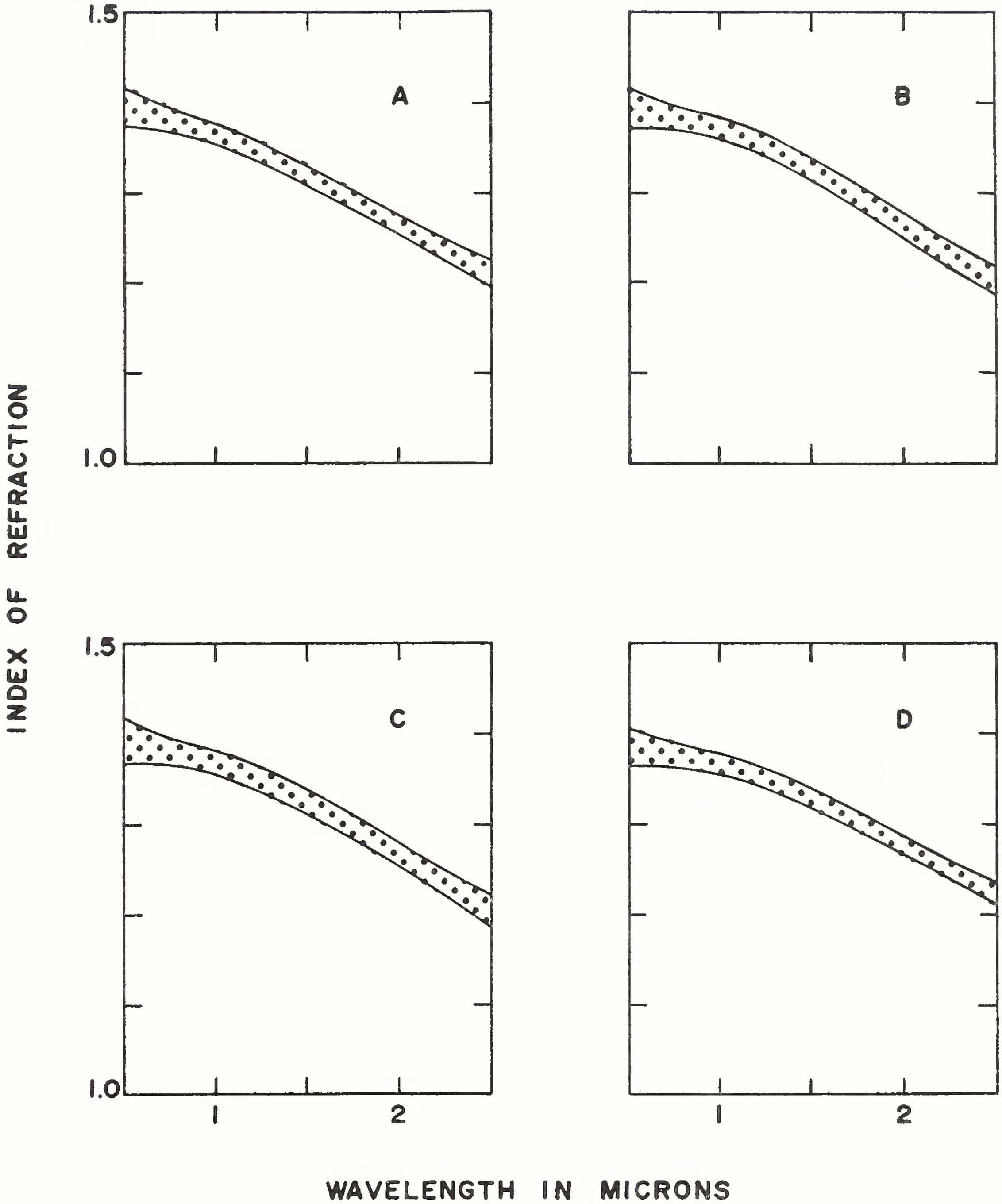
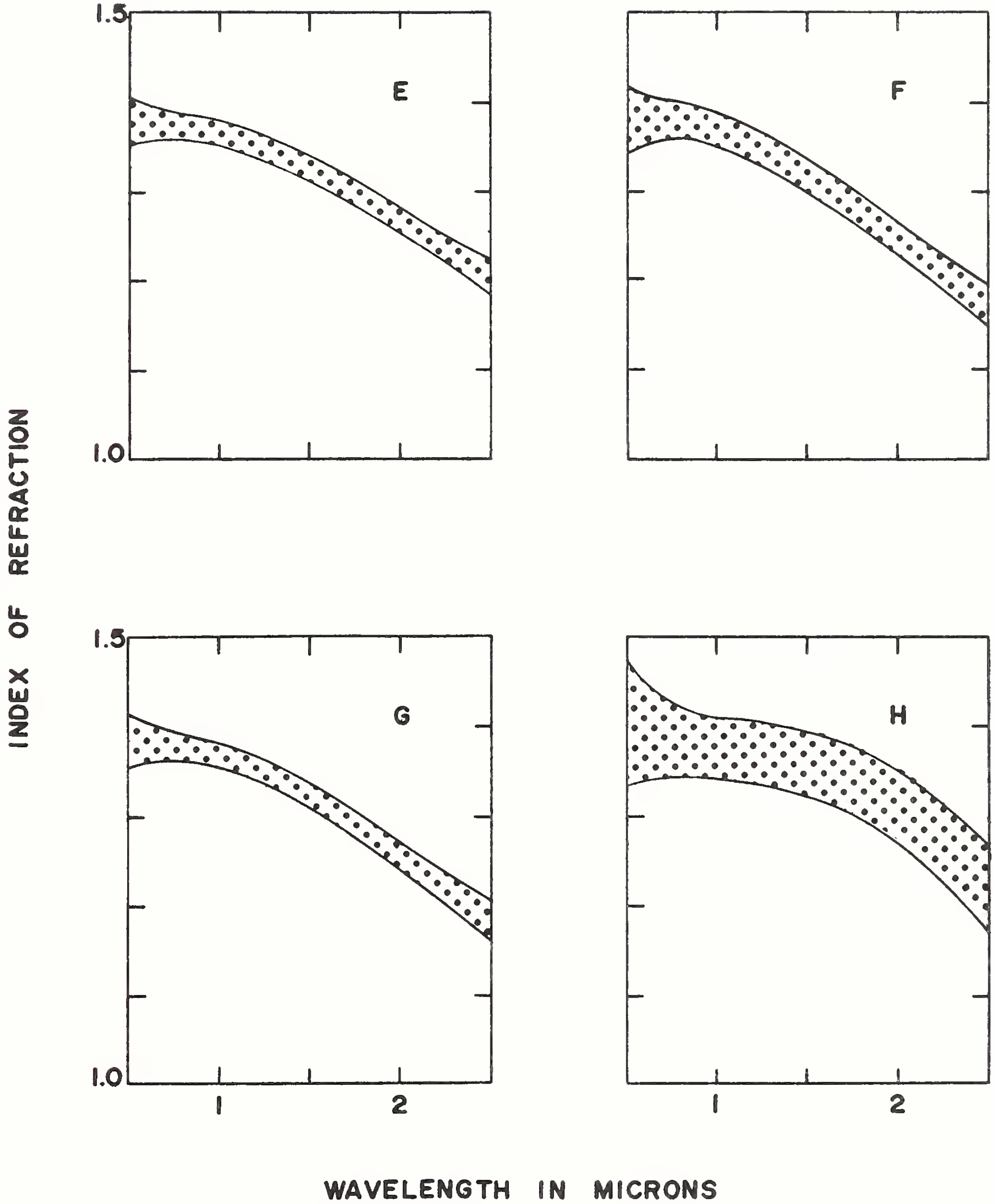


Fig. 6. Dispersion curves for (A) corn; (B) watermelon; (C) orange; (D) sunflower; (E) peach; (F) cotton; (G) okra; (H) onion; (I) avocado; (J) pigweed; (K) sugarcane; (L) pumpkin; (M) tomato; (N) cantaloupe; (O) bean; (P) sorghum (Q) pepper; (R) soybean; (S) lettuce; and (T) wheat.



INDEX OF REFRACTION
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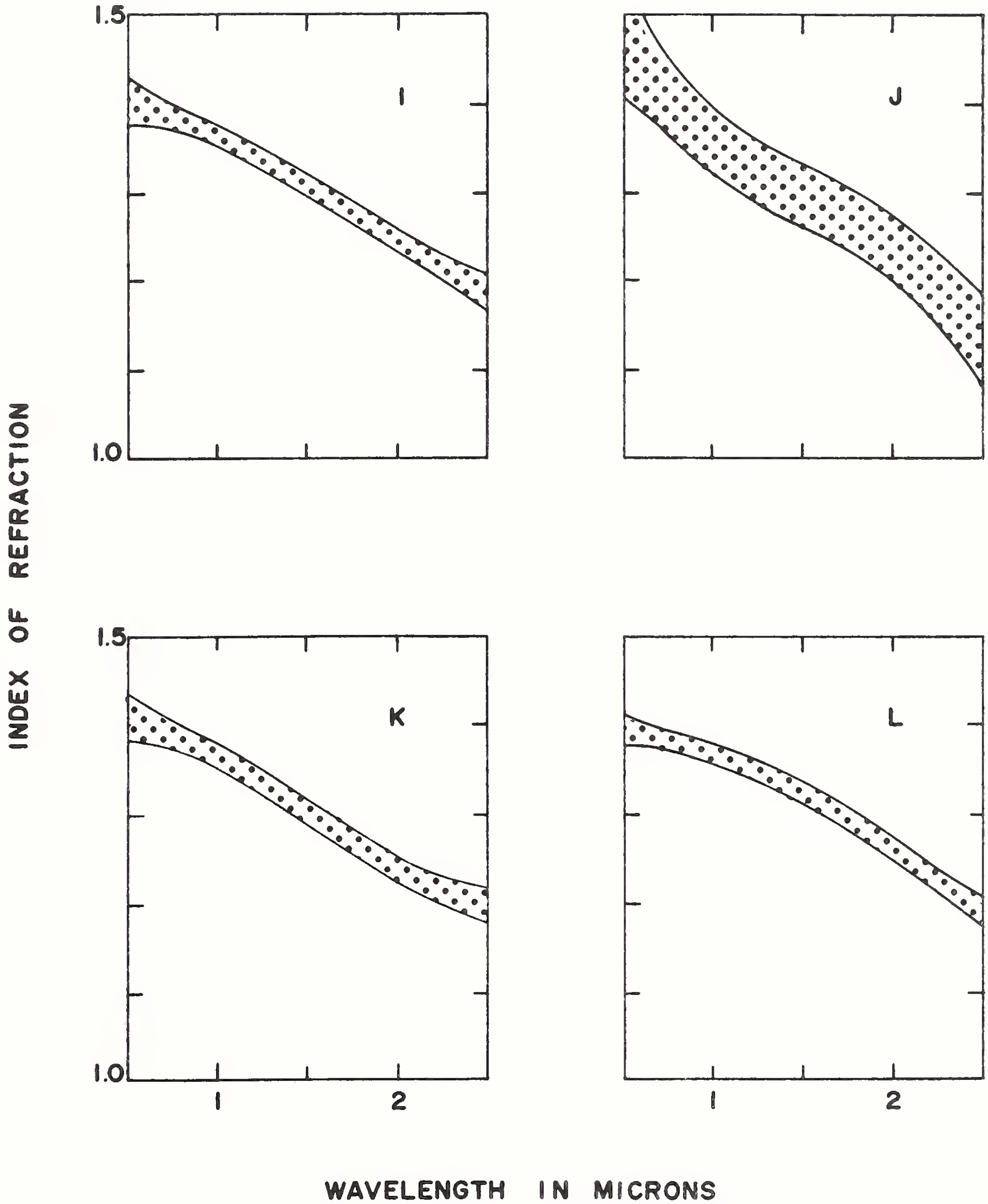
1.0
E
F
G
H
1
2
WAVELENGTH IN MICRONS



INDEX OF REFRACTION
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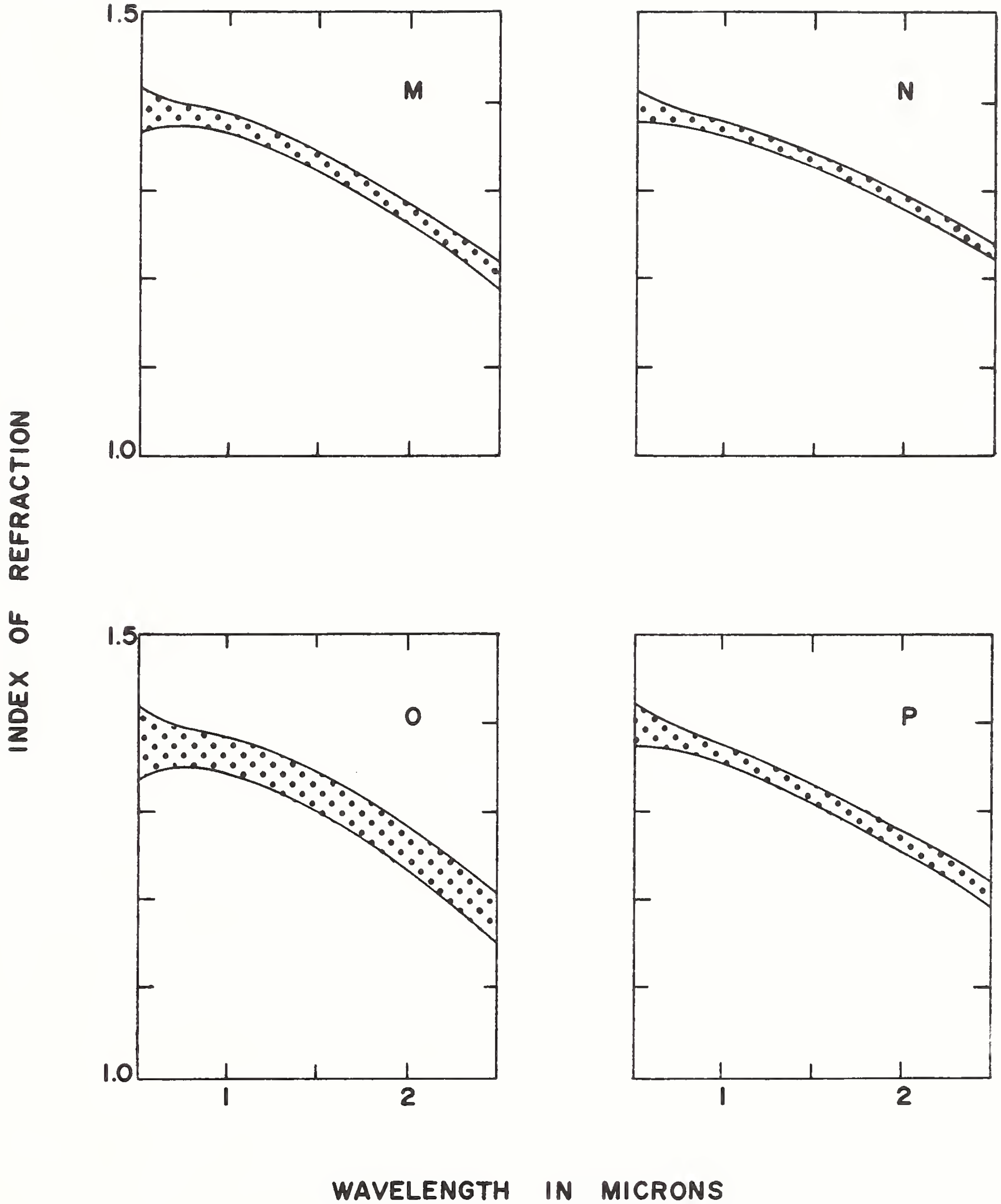
1.0
I
J
K
L
1
2
WAVELENGTH IN MICRONS



INDEX OF REFRACTION
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M
N
1.5
1.0
O
P
1
2
1
2
WAVELENGTH IN MICRONS

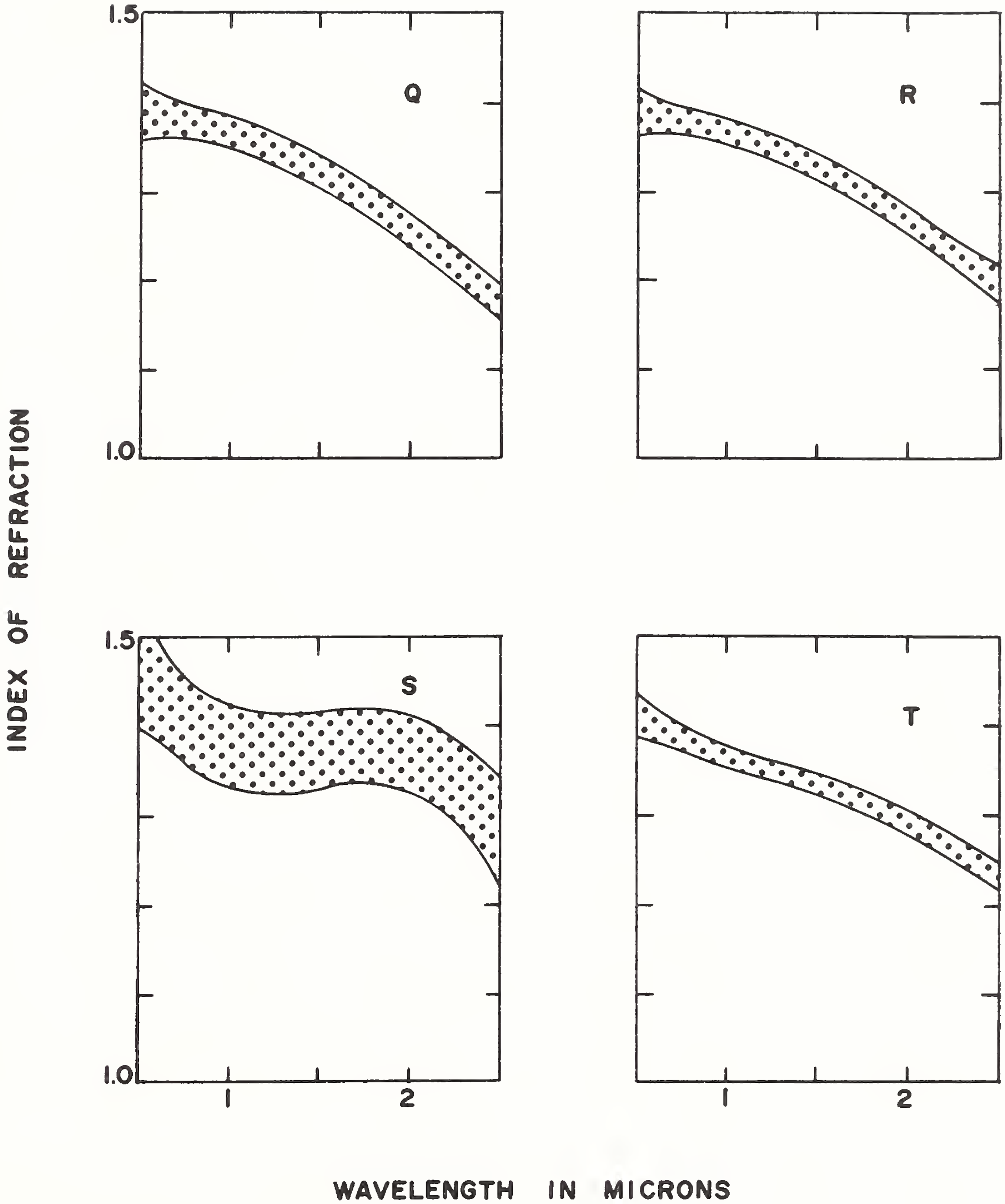
INDEX OF REFRACTION
1.5
1.0
Q
R
S
T
1
2
WAVELENGTH IN MICRONS

Table 8. Coefficients of dispersion curve $n = \Sigma a_i \lambda^i$ for leaves of 20 crops where λ is expressed in micrometers.

Crop	a_0	a_1	a_2	a_3
Corn	1.403	0.017	-0.065	0.011
Watermelon	1.377	0.076	-0.098	0.016
Orange	1.390	0.037	-0.071	0.010
Sunflower	1.355	0.110	-0.116	0.020
Peach	1.347	0.117	-0.115	0.018
Pumpkin	1.406	0.011	-0.058	0.007
Sugarcane	1.402	0.079	-0.145	0.032
Pigweed	1.721	-0.626	0.334	-0.071
Avocado	1.398	0.063	-0.120	0.025
Onion	1.481	-0.217	0.156	-0.044
Okra	1.347	0.134	-0.134	0.022
Cotton	1.320	0.196	-0.177	0.030
Tomato	1.379	0.062	-0.078	0.010
Cantaloupe	1.425	-0.062	0.013	-0.008
Bean	1.365	0.059	-0.067	0.006
Sorghum	1.408	0.004	-0.055	0.009
Pepper	1.393	0.005	-0.031	-0.003
Soybean	1.394	0.003	-0.023	0.127
Lettuce	1.792	-0.878	0.587	-0.127
Wheat	1.487	-0.185	0.085	-0.021

Table 9. Parameters that specify amount of H_2O and intercellular air space in leaves of 20 crops. Table headings are defined elsewhere[a].

Crop	D(μm)	N	D/N	R_∞[b](%)	S.E.
Corn	173	1.44	119.6	41.8 ± 0.8	.013
Watermelon	203	1.59	127.8	39.9 ± 0.9	.018
Orange	209	2.27	91.9	44.7 ± 0.5	.019
Sunflower	242	1.54	157.1	36.9 ± 0.5	.017
Peach	119	1.65	72.0	50.3 ± 0.5	.019
Pumpkin	152	1.48	102.3	44.0 ± 0.5	.017
Sugarcane	224	1.55	144.1	36.4 ± 0.5	.022
Pigweed	173	1.43	121.1	41.0 ± 0.4	.017
Avocado	190	1.73	109.3	40.8 ± 0.7	.022
Onion	606	1.13	533.6	18.5 ± 0.6	.094
Okra	181	1.65	109.5	42.6 ± 0.7	.017
Cotton	199	1.52	130.8	39.7 ± 0.4	.016
Tomato	260	1.70	152.7	36.6 ± 0.8	.019
Cantaloupe	239	1.56	152.8	37.6 ± 0.5	.016
Bean	219	2.20	99.5	46.9 ± 0.5	.015
Sorghum	101	1.51	67.0	50.7 ± 0.7	.018
Pepper	189	1.76	107.3	44.4 ± 0.6	.015
Soybean	111	1.45	76.8	50.8 ± 1.0	.015
Lettuce	524	1.05	499.7	17.6 ± 1.5	.018
Wheat	169	1.82	92.4	45.6 ± 0.8	.017

[a] Allen, Gausman, and Richardson (1970).

[b] At 1.65 μm WL.

As indicated previously (Allen et al., 1969, 1970a, 1970b), the quantities D/N and R_∞ are strongly correlated. Figure 7 indicates the relationship. The quantity D and the leaf thickness are also correlated with R_∞. The thinner the leaf the greater will be reflectance produced by a pile of such leaves. This fact has important implications in the interpretation of remote sensing data.

Table 10 is a compilation of the mean absorption spectra in cm^{-1} units over the range 1.4 to 2.5 μm for the leaves of 20 crops. These values correlate (r = 0.998) with those previously obtained (Allen et al., 1970b) on other leaves of agricultural interest. The published values for pure liquid H_2O are also presented in Table 10 for comparative purposes. Figures 8 and 8a are comparisons of experimental and computed values of leaf H_2O thickness obtained by procedures previously discussed (Gausman et al., 1970). The shaded portions on the bar graphs represent plus or minus one standard deviation. All data are plotted for the laboratory H_2O determinations that were made on entire leaves. Sugarcane, corn, sorghum, and wheat leaves are not included in Fig. 8 and 8a. Their thickness and H_2O content determinations in the laboratory were made on sections of entire leaves. With the exception of pumpkin, avocado, okra, tomato, cantaloupe, and lettuce, there is no statistically significant difference between H_2O obtained experimentally and H_2O determined theoretically. However, none of the six exceptions exhibit a highly statistically significant difference (unpaired t test) between observed and computed values for leaf H_2O.

Table 11 includes the absorption spectra, over the 0.5- to 1.3-μm range, for 11 kinds of plant leaves (first 11 entries) reported in an earlier paper (Gausman et al., 1971) plus the 20 (last 20 entries) crop leaves introduced in the present paper. Note that corn appears twice--once in the earlier work and then in the 20 leaves reported in this paper.

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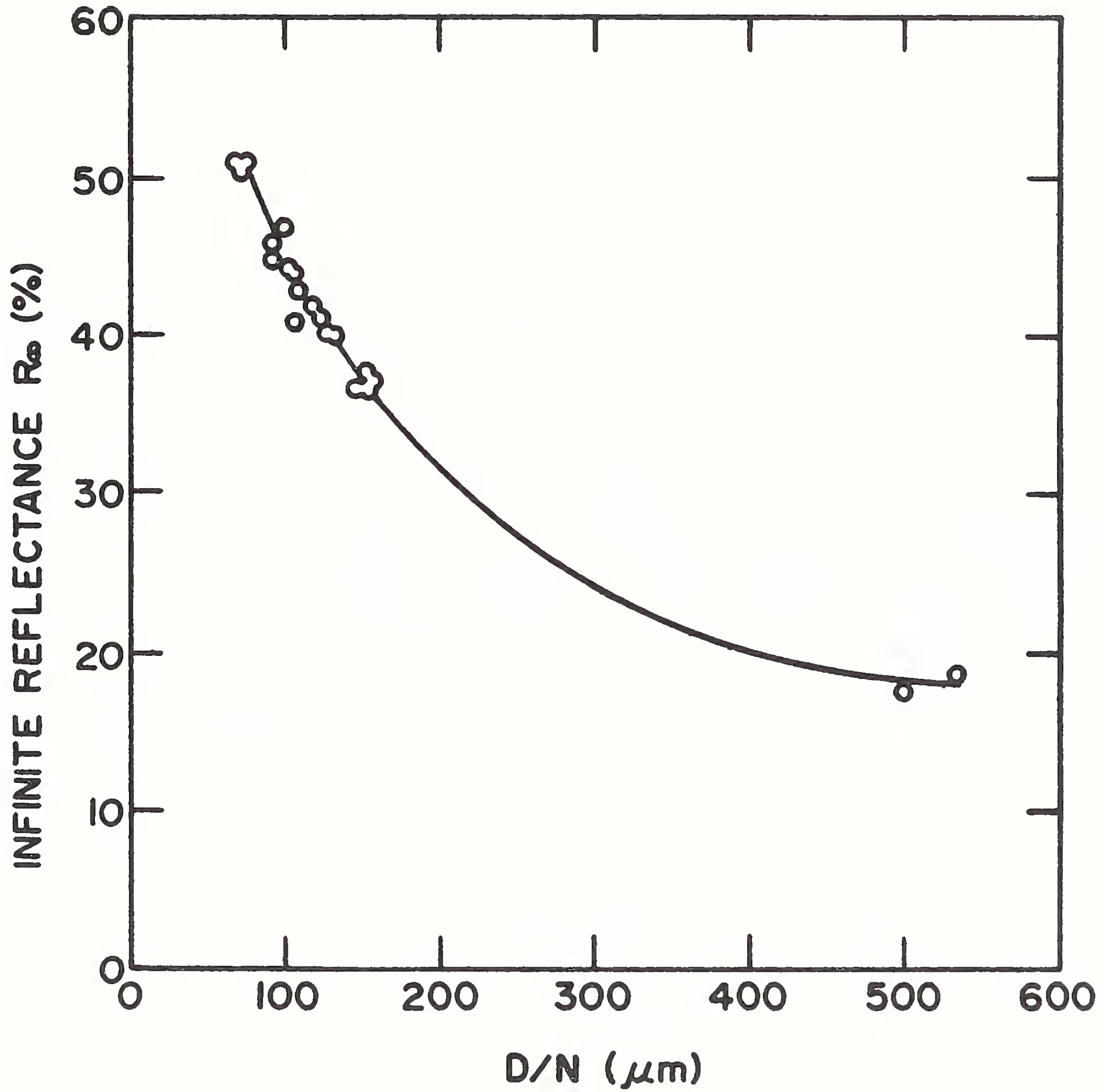

Fig. 7. Infinite reflectance R_∞ at 1.65 μm for 20 genera of plant leaves plotted as function of characteristic linear dimension D/N.

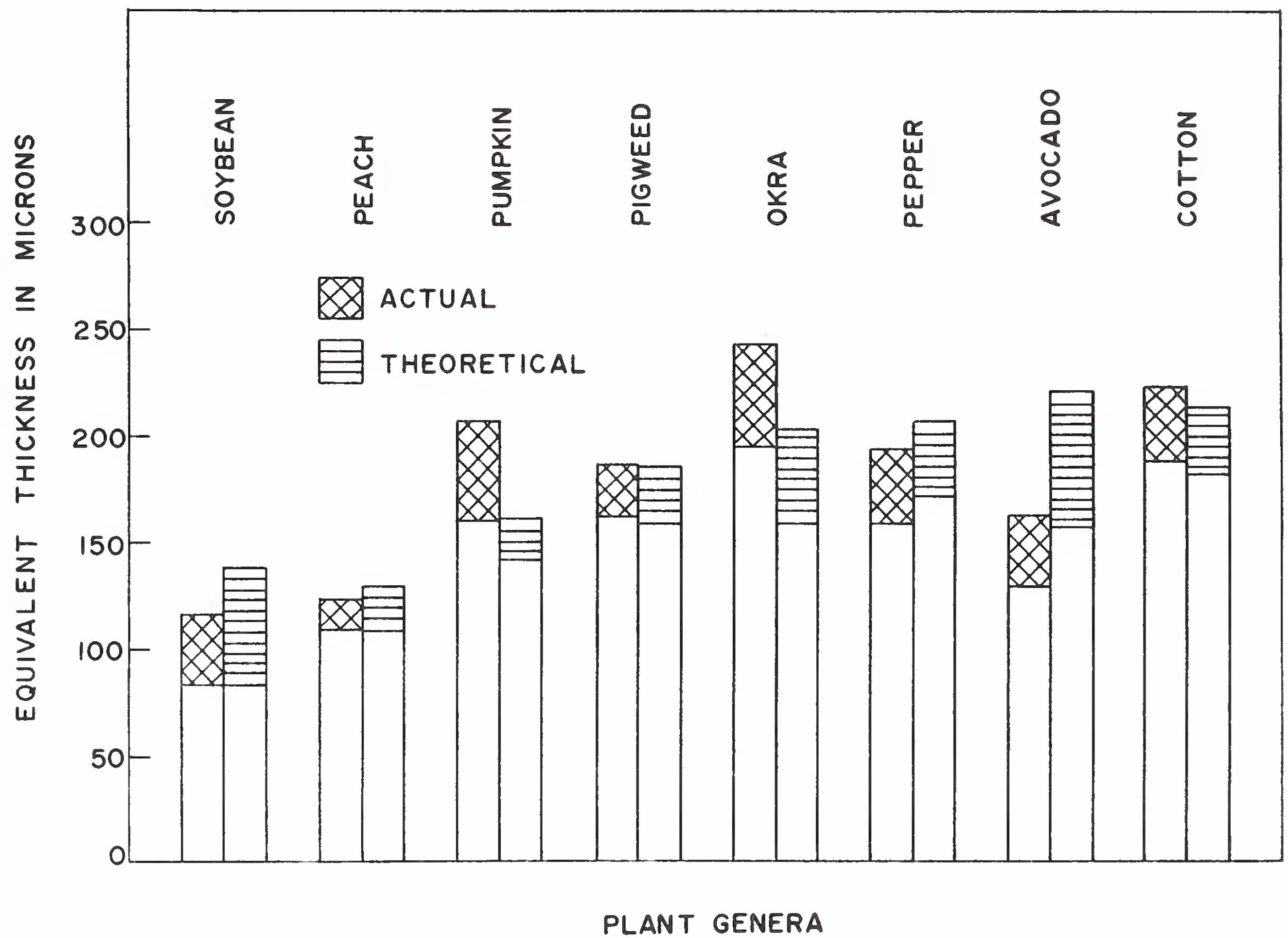

Fig. 8. Comparison of observed and computed values of effective H_2O thickness of leaves. The shaded areas represent a variation of one standard deviation.

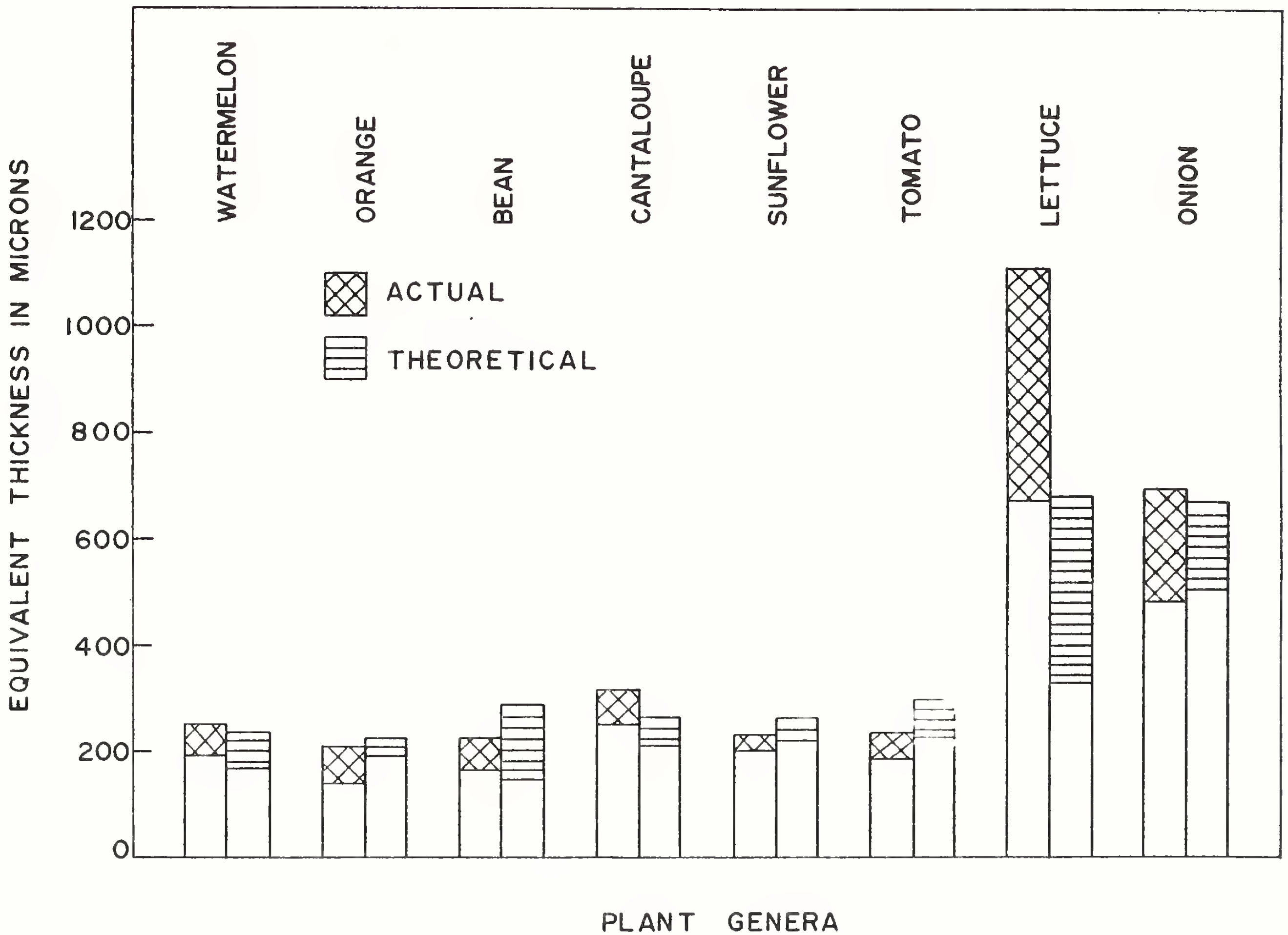

Fig. 8a. Comparison of observed and computed values of effective H_2O thickness of leaves. The shaded areas represent a variation of one standard deviation.

Table 10. Mean[a] absorption spectra in cm^{-1} units over the 1.4- to 2.5-μm range of the leaves of 20 crops compared with published values for pure liquid H_2O[b].

Wavelength (μm)	Leaf	Water
1.40	14.3 ± 1.0	12.5
1.45	24.6 ± 2.0	25.8
1.50	16.5 ± 1.5	18.5
1.55	9.9 ± 0.3	9.8
1.60	6.8 ± 0.3	6.5
1.65	5.6 ± 0.3	5.1
1.70	5.8 ± 0.4	5.2
1.75	7.2 ± 0.4	6.0
1.80	8.1 ± 0.3	8.1
1.85	15.5 ± 1.0	9.8
1.90	58.7 ± 6.4	81.0
1.95	77.9 ± 18.7	106.0
2.00	49.5 ± 3.2	68.0
2.05	33.7 ± 1.9	43.0
2.10	24.2 ± 0.6	26.0
2.15	19.3 ± 0.7	19.0
2.20	17.6 ± 0.6	16.0
2.25	20.3 ± 0.8	18.0
2.30	26.4 ± 1.0	22.0
2.35	34.8 ± 0.7	31.0
2.40	46.3 ± 1.9	43.0
2.45	59.8 ± 1.9	60.0
2.50	70.0 ± 4.2	83.0

a Each kind of leaf was assigned a statistical weight of unity.

b Curcio and Petty (1951).

Table 11. Absorption spectra in cm^{-1} units over the 0.5- to 1.3-μm range for 31 kinds of plant leaves. The first 11 entries have been reported previously (Gausman et al., 1971).

	Wavelength (μm)								
Plant leaf	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Eucalyptus	56.3	61.0	9.7	0.7	0.6	0.6	0.5	1.2	1.6
Banana	55.2	60.2	9.7	0.4	0.4	0.5	0.5	1.2	1.7
Rose	108.1	128.8	18.9	0.6	0.5	0.5	0.5	1.0	1.5
Ligustrum	44.9	48.7	5.7	0.3	0.3	0.4	0.4	1.1	1.5
Ficus	45.5	48.1	5.9	0.3	0.3	0.4	0.4	1.1	1.6
Oleander	54.7	57.6	9.7	0.8	0.7	0.8	0.7	1.4	1.7
Crinum	29.5	29.5	4.6	0.3	0.3	0.5	0.4	1.2	1.7
Begonia	21.6	19.3	3.0	0.2	0.2	0.3	0.3	1.0	1.6
Hyacinth	42.7	47.3	7.7	0.4	0.3	0.4	0.3	1.0	1.6
Corn	76.2	81.7	15.7	0.7	0.6	0.6	0.5	1.2	1.7
Sedum	10.4	10.2	2.0	0.1	0.1	0.3	0.2	1.0	1.5
Corn	70.2	79.1	15.0	0.5	0.4	0.5	0.5	1.2	1.7
Watermelon	52.0	62.0	8.7	0.9	0.8	0.7	0.7	1.4	2.0
Orange	103.6	121.3	14.4	0.8	0.8	0.7	0.7	1.4	1.8
Sunflower	45.0	50.6	8.6	0.5	0.5	0.5	0.5	1.1	1.7
Peach	112.1	137.1	17.0	0.7	0.7	0.6	0.6	1.2	1.7
Pumpkin	74.2	84.7	13.4	0.9	0.7	0.7	0.6	1.3	1.8
Sugarcane	30.2	37.0	8.4	0.8	0.8	0.9	0.9	1.6	2.1
Pigweed	54.7	78.3	13.5	0.4	0.4	0.4	0.4	1.1	1.7
Avocado	98.0	121.8	13.7	0.7	0.6	0.6	0.6	1.3	1.7
Onion	13.4	15.6	2.8	0.2	0.2	0.4	0.4	1.1	1.7
Okra	54.7	61.8	11.2	0.7	0.6	0.6	0.6	1.3	1.8
Cotton	48.6	58.0	9.2	0.5	0.5	0.6	0.6	1.2	1.8
Tomato	59.2	82.0	9.2	0.9	0.8	0.8	0.8	1.4	2.1
Cantaloupe	44.4	54.3	8.3	0.5	0.4	0.4	0.5	1.1	1.8
Bean	36.2	46.2	7.1	0.1	0.2	0.2	0.2	0.9	1.6
Sorghum	82.6	102.1	20.8	0.9	0.7	0.7	0.6	1.3	1.8
Pepper	46.3	53.5	8.8	0.3	0.3	0.3	0.3	1.0	1.6
Soybean	74.5	91.4	15.0	0.5	0.4	0.4	0.4	1.1	1.6
Lettuce	2.6	2.7	1.0	0.4	0.5	0.6	0.6	1.6	2.3
Wheat	105.7	108.3	16.3	0.8	0.7	0.7	0.6	1.3	1.8

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APPENDIX TABLE OF CONTENTS FOR FIGURES

The Table of Contents below gives the page number in the Appendix that the reflectance, transmittance, and absorptance spectra of each of the 20 crops can be found for the 500- to 2500-nm WLI. Each spectrum is an average of values for 10 leaves (replications). The crop and corresponding figure number is noted in the upper left hand corner of each figure.

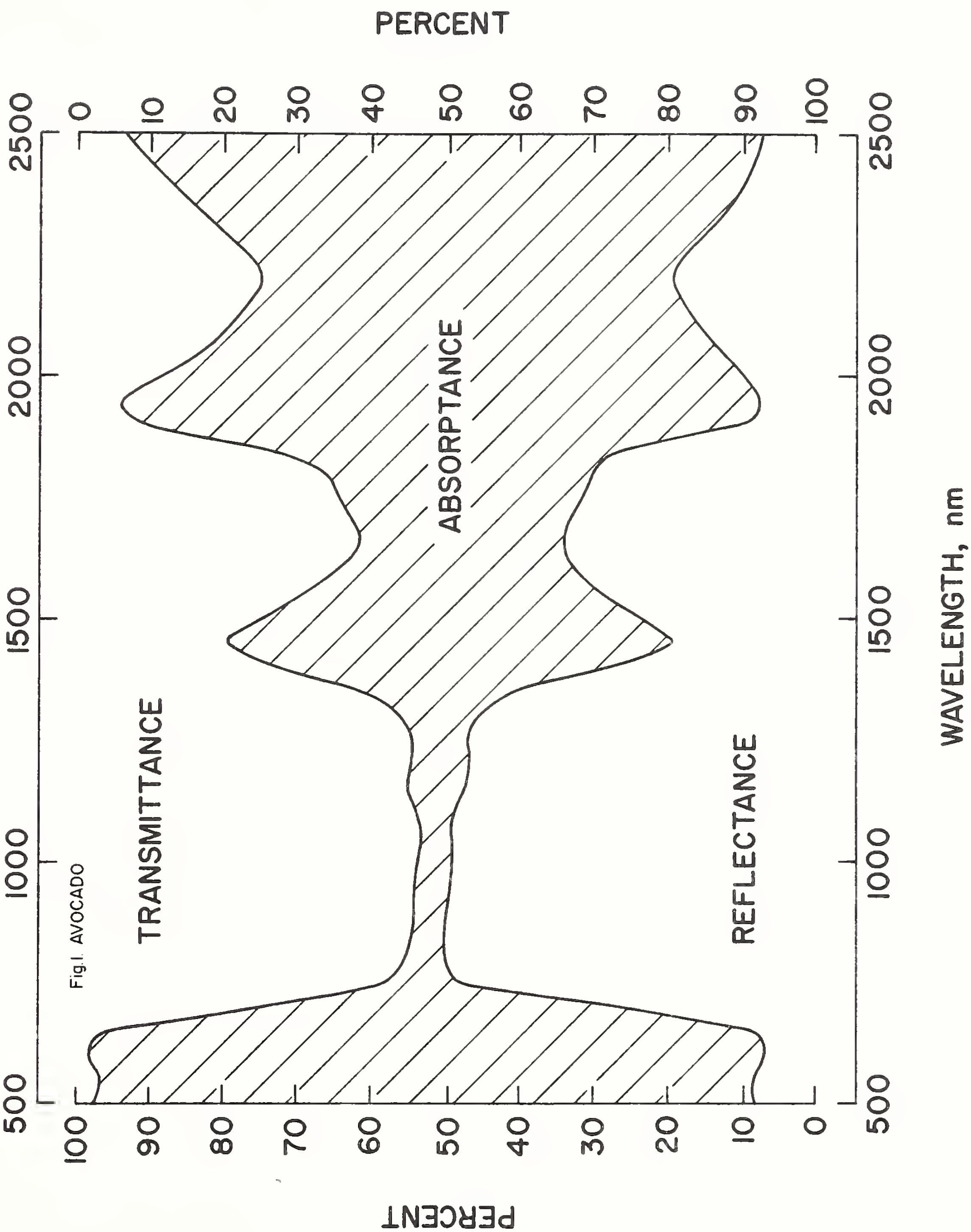


Fig.1. AVOCADO

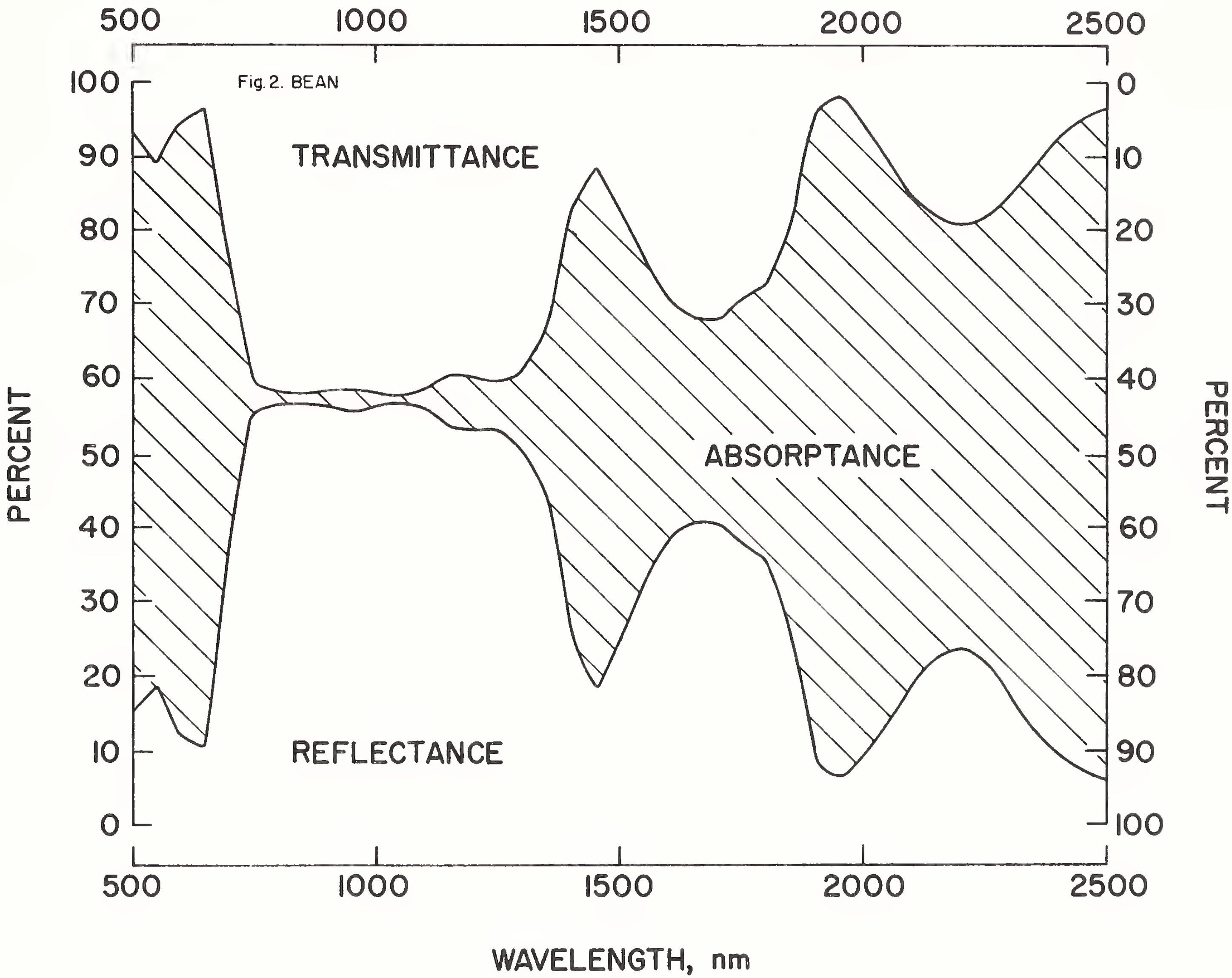


Fig. 2. BEAN
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
PERCENT
PERCENT
WAVELENGTH, nm
500
1000
1500
2000
2500
100
90
80
70
60
50
40
30
20
10
0

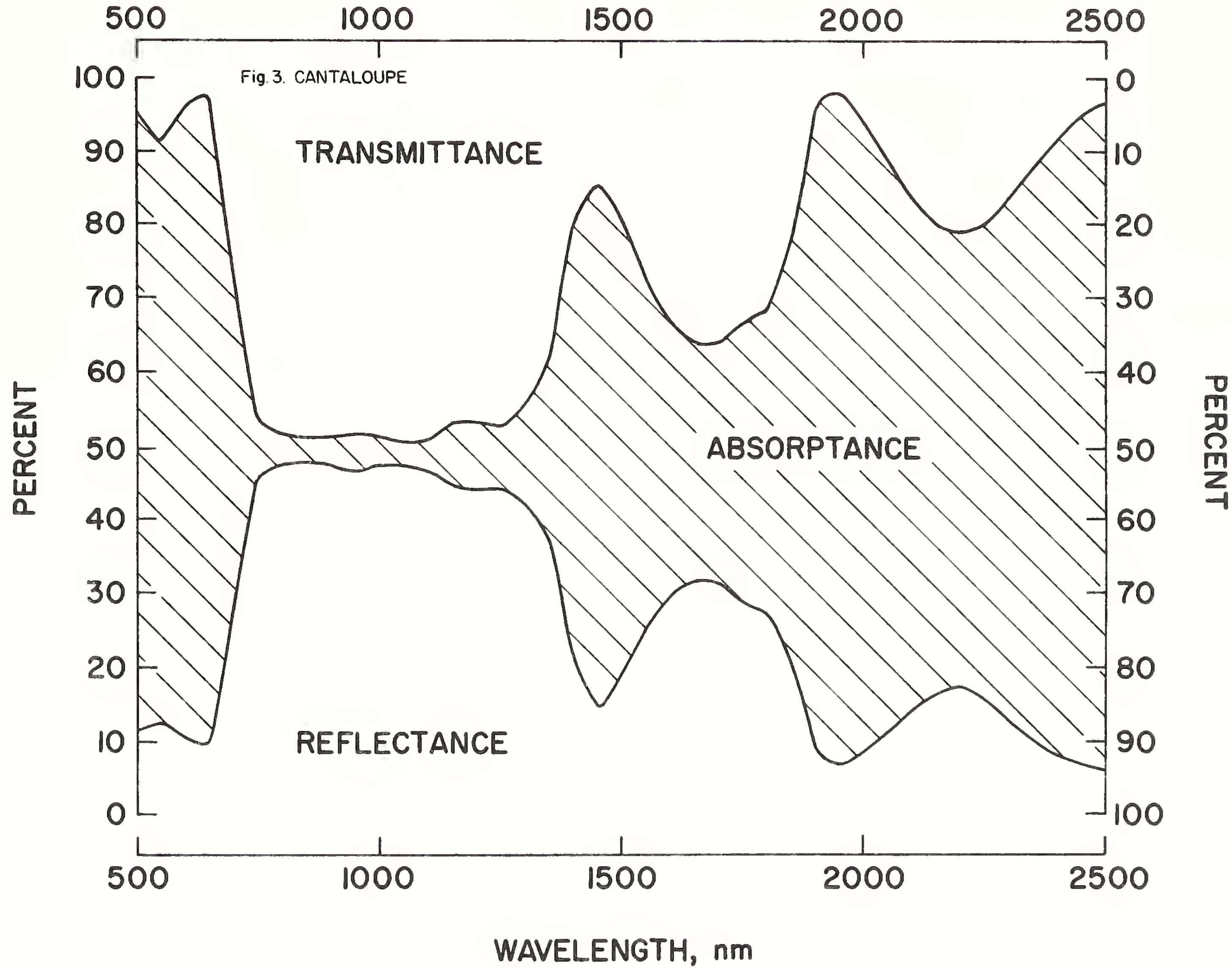


Fig. 3. CANTALOUPE
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
PERCENT
PERCENT
WAVELENGTH, nm
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100

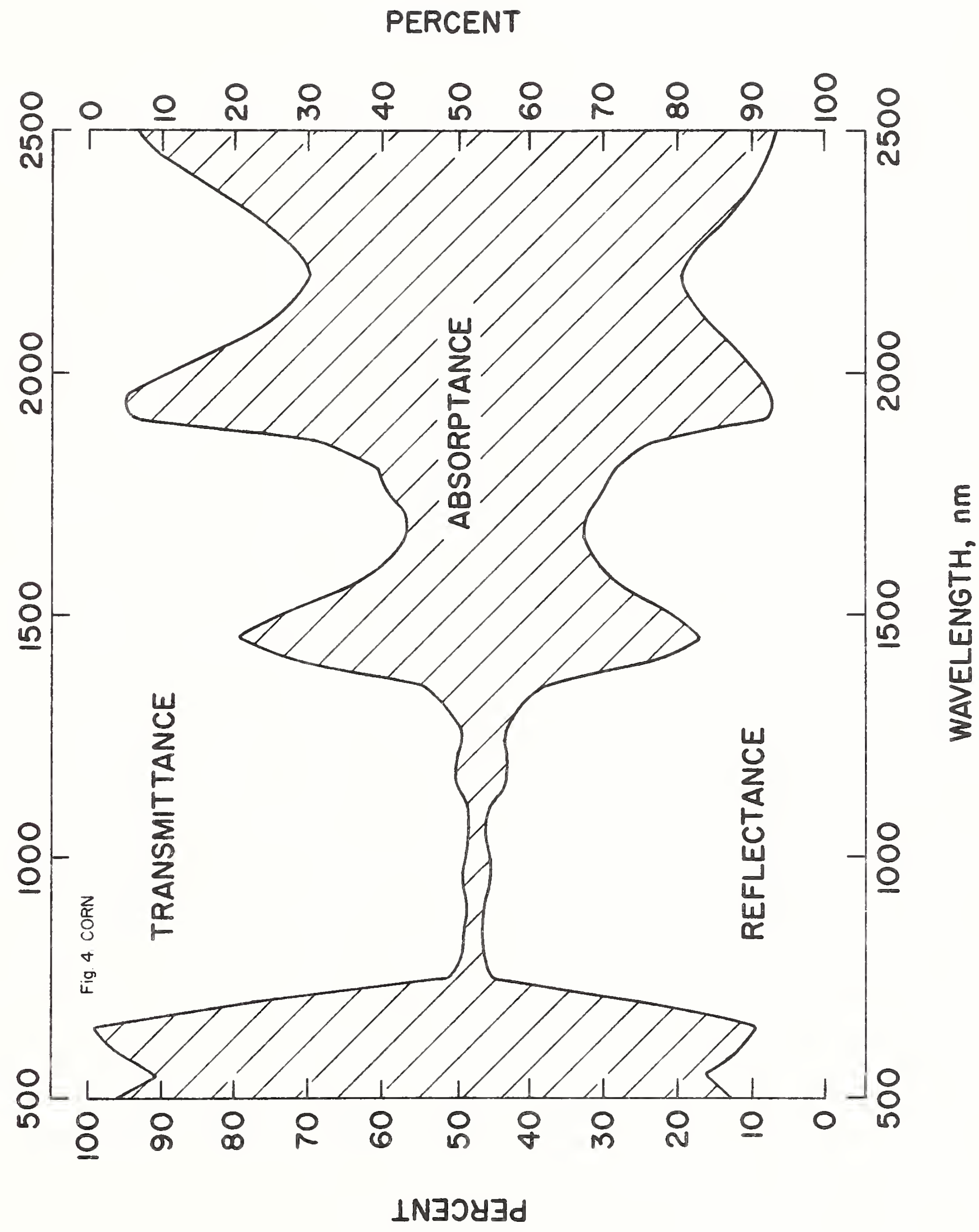

PERCENT
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
WAVELENGTH, nm
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100

Fig. 4 CORN

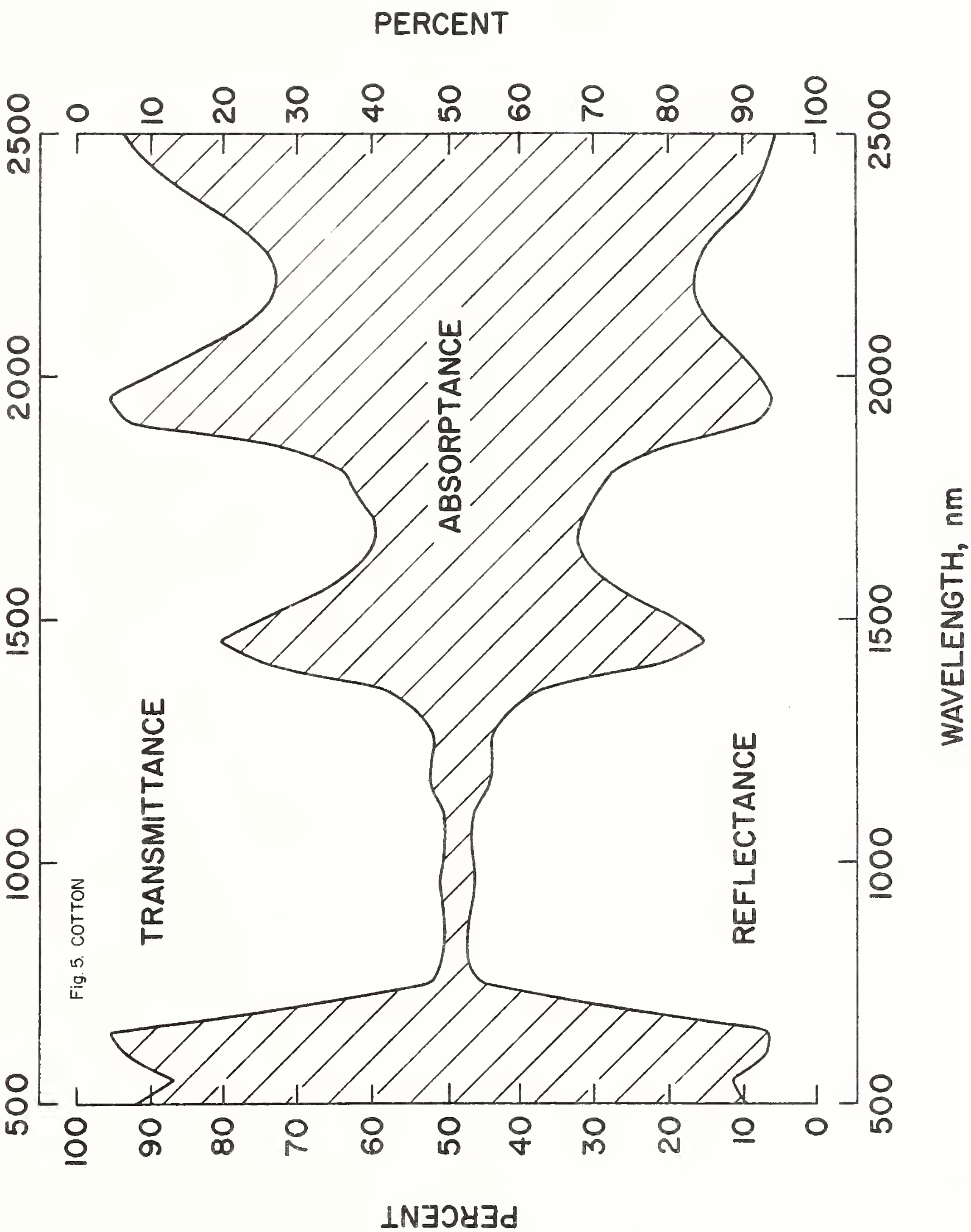

PERCENT
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
WAVELENGTH, nm
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100

Fig. 5. COTTON

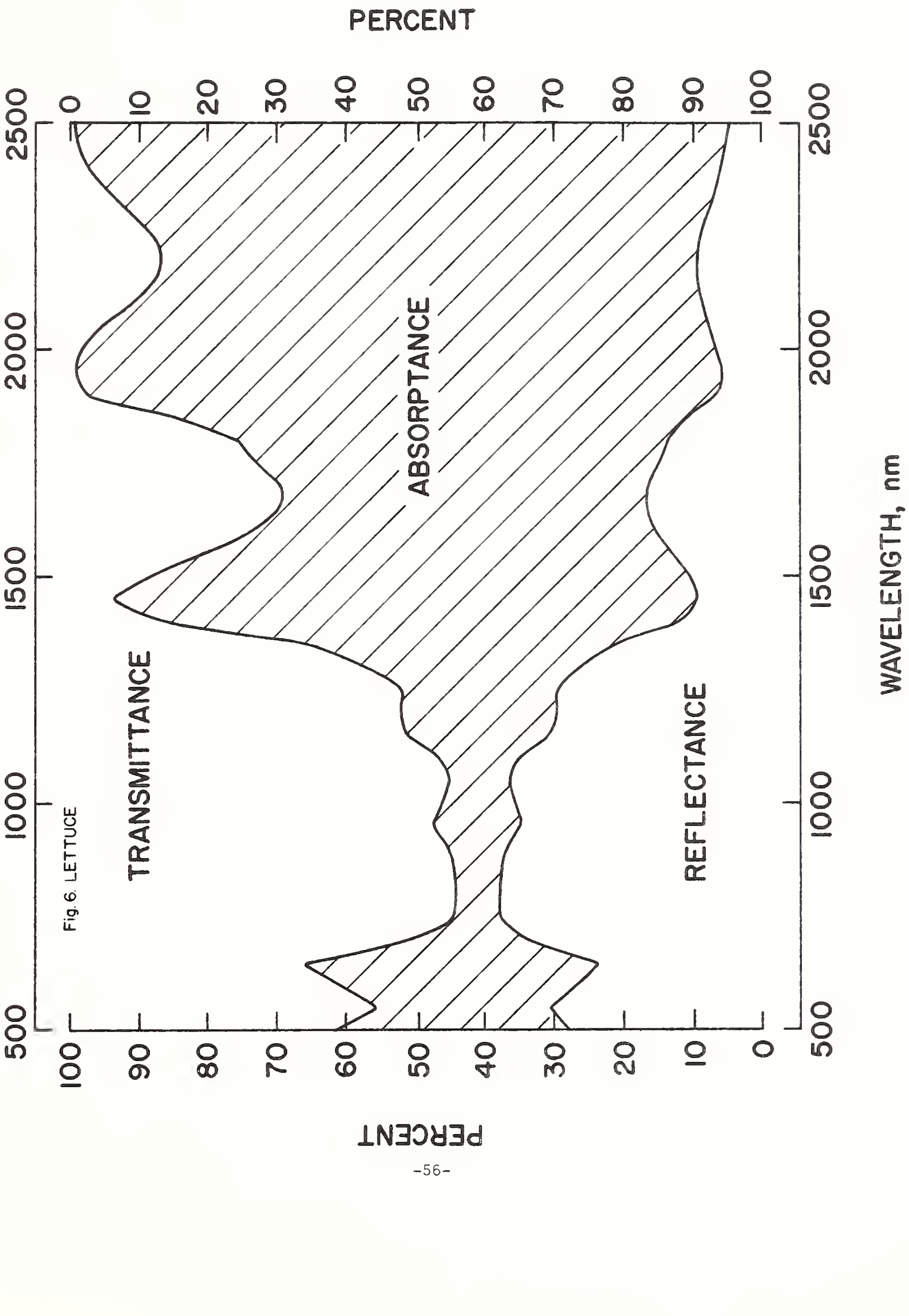


Fig. 6. LETTUCE

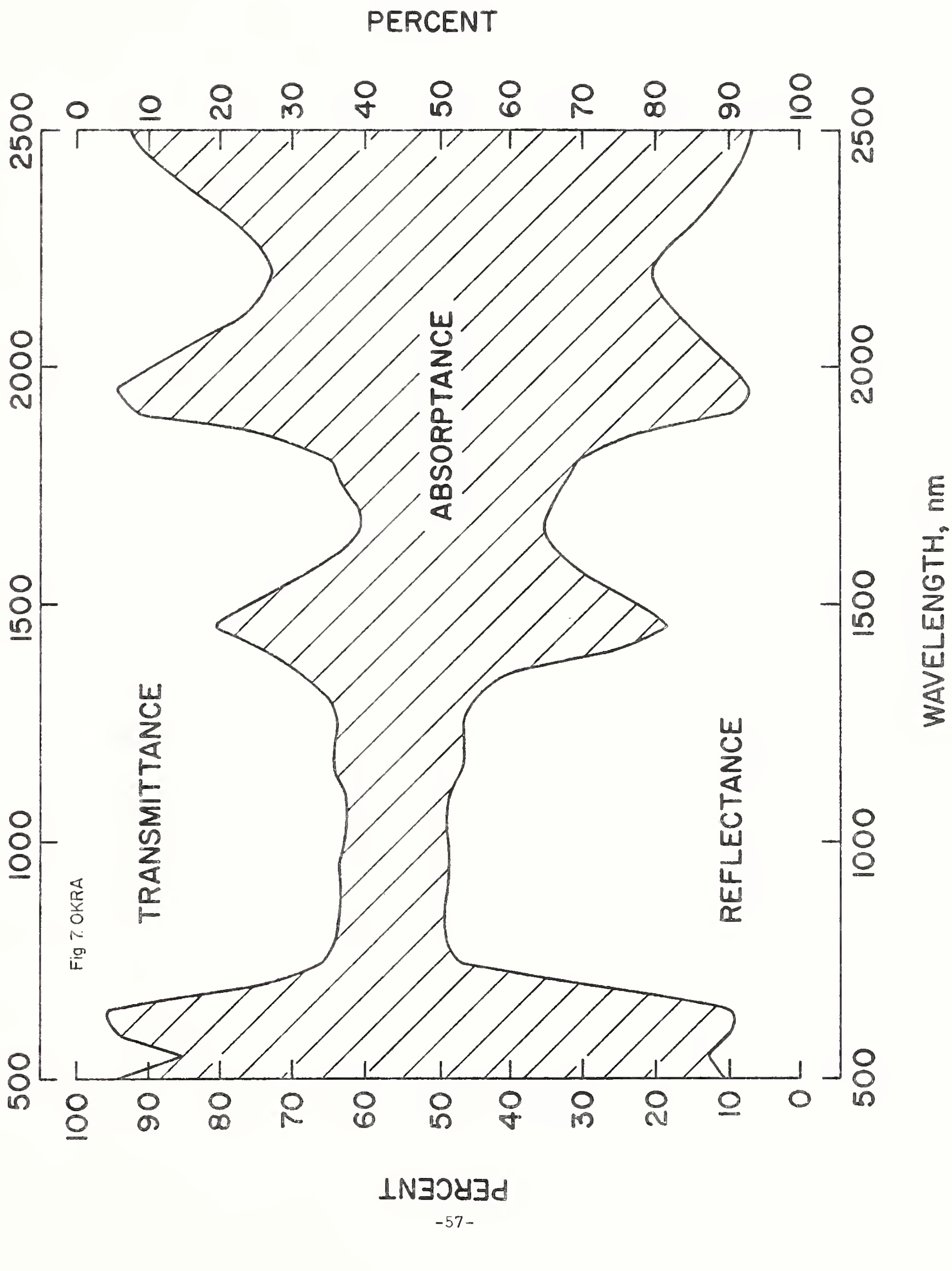


Fig 7. OKRA
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
WAVELENGTH, nm
PERCENT
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100
PERCENT

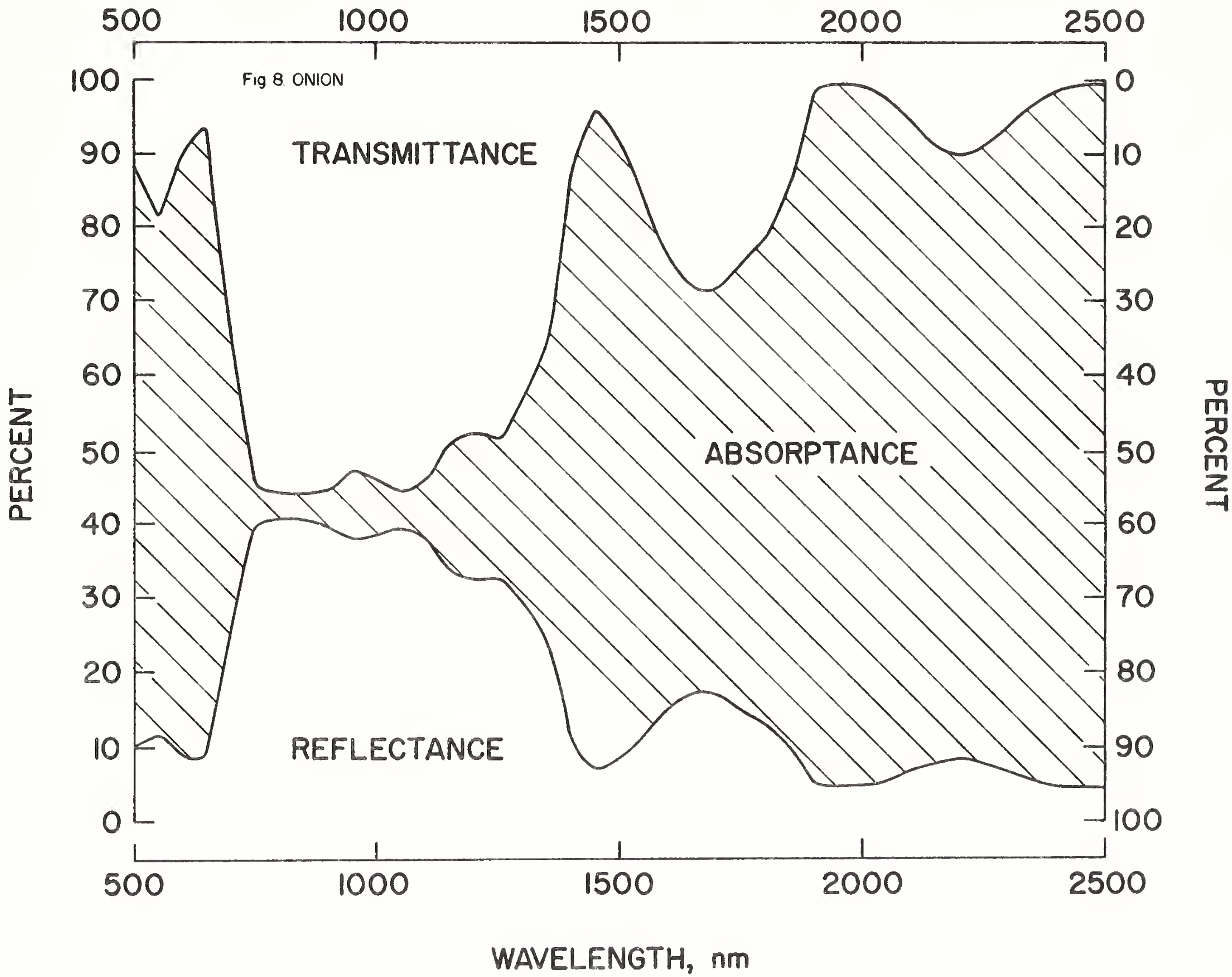

TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
PERCENT
PERCENT
WAVELENGTH, nm
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100

Fig 8. ONION

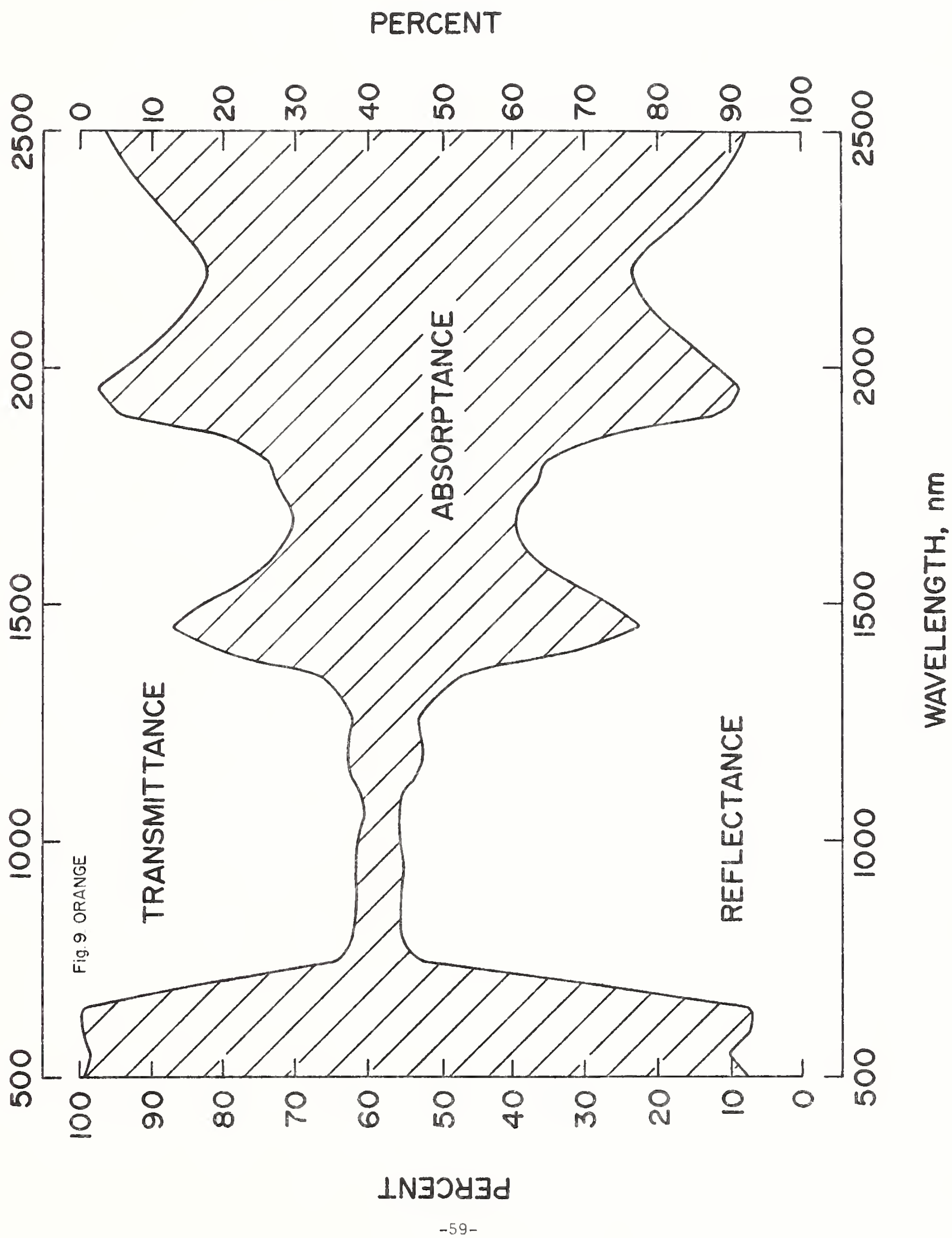

PERCENT
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
WAVELENGTH, nm
500
1000
1500
2000
2500
0
10
20
30
40
50
60
70
80
90
100
PERCENT

Fig. 9 ORANGE

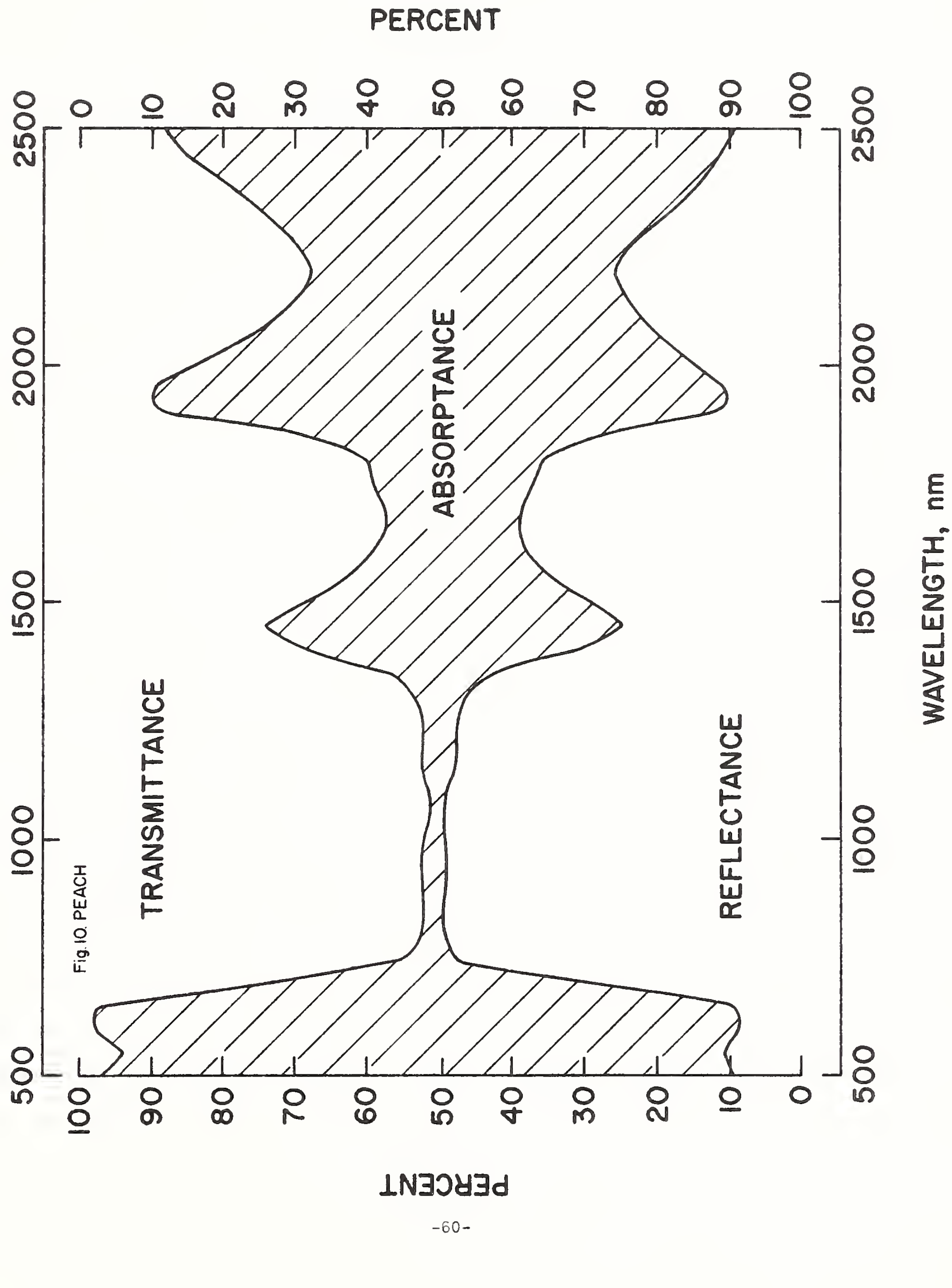


Fig.10 PEACH
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
PERCENT
0
10
20
30
40
50
60
70
80
90
100
PERCENT
100
90
80
70
60
50
40
30
20
10
0
500
1000
1500
2000
2500
WAVELENGTH, nm

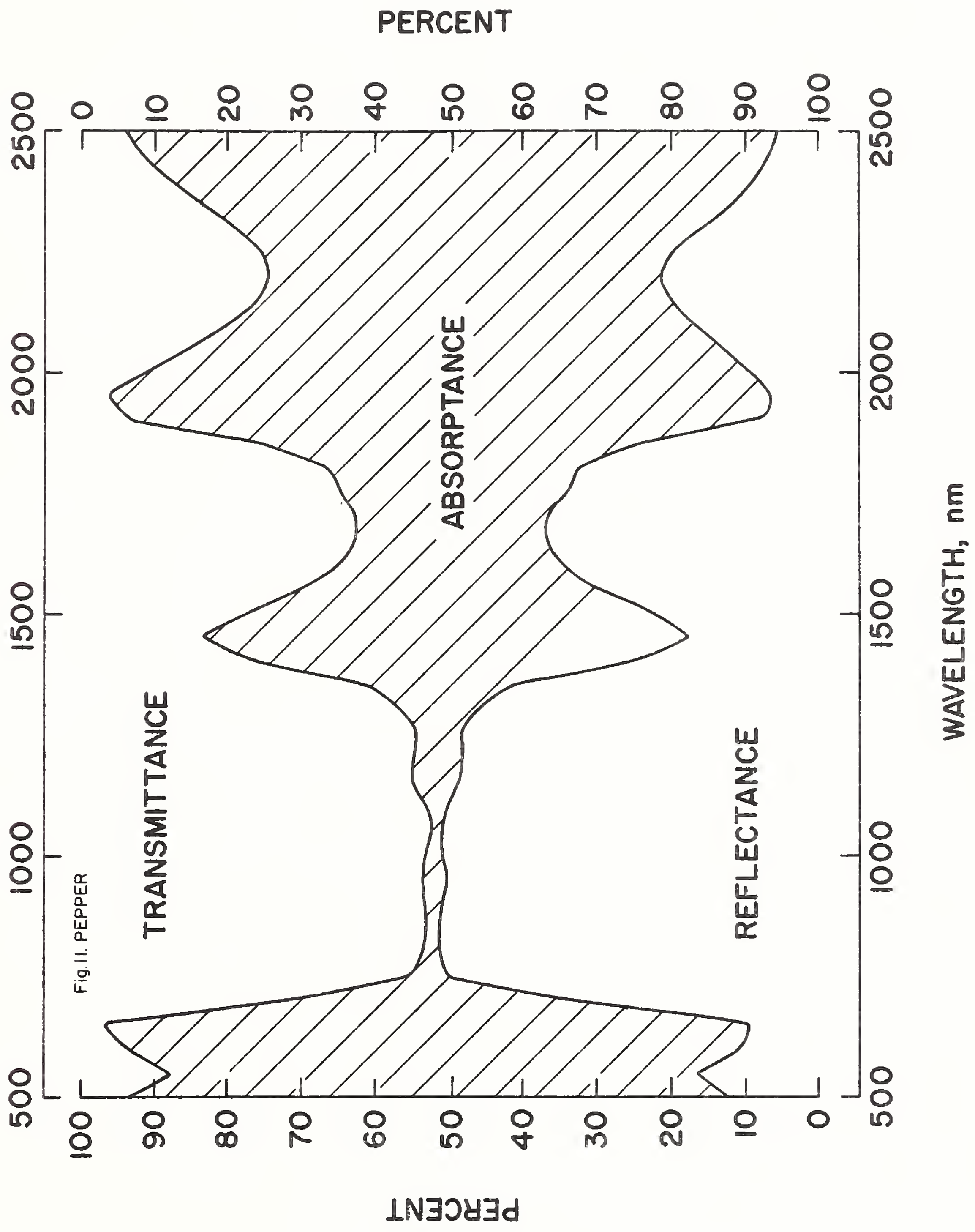


Fig.11. PEPPER
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
PERCENT
0 10 20 30 40 50 60 70 80 90 100
100 90 80 70 60 50 40 30 20 10 0
500 1000 1500 2000 2500
WAVELENGTH, nm

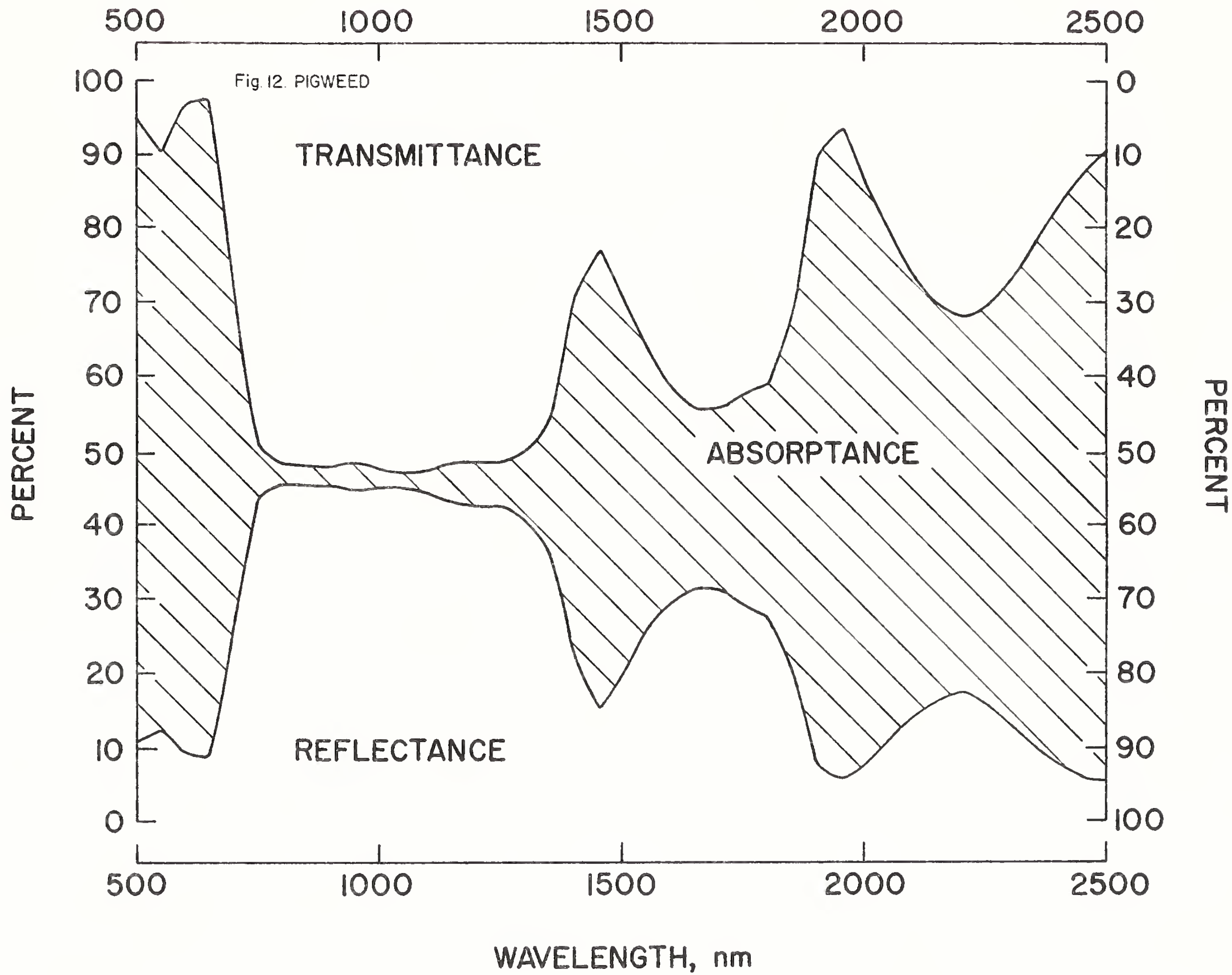


Fig. 12. PIGWEED

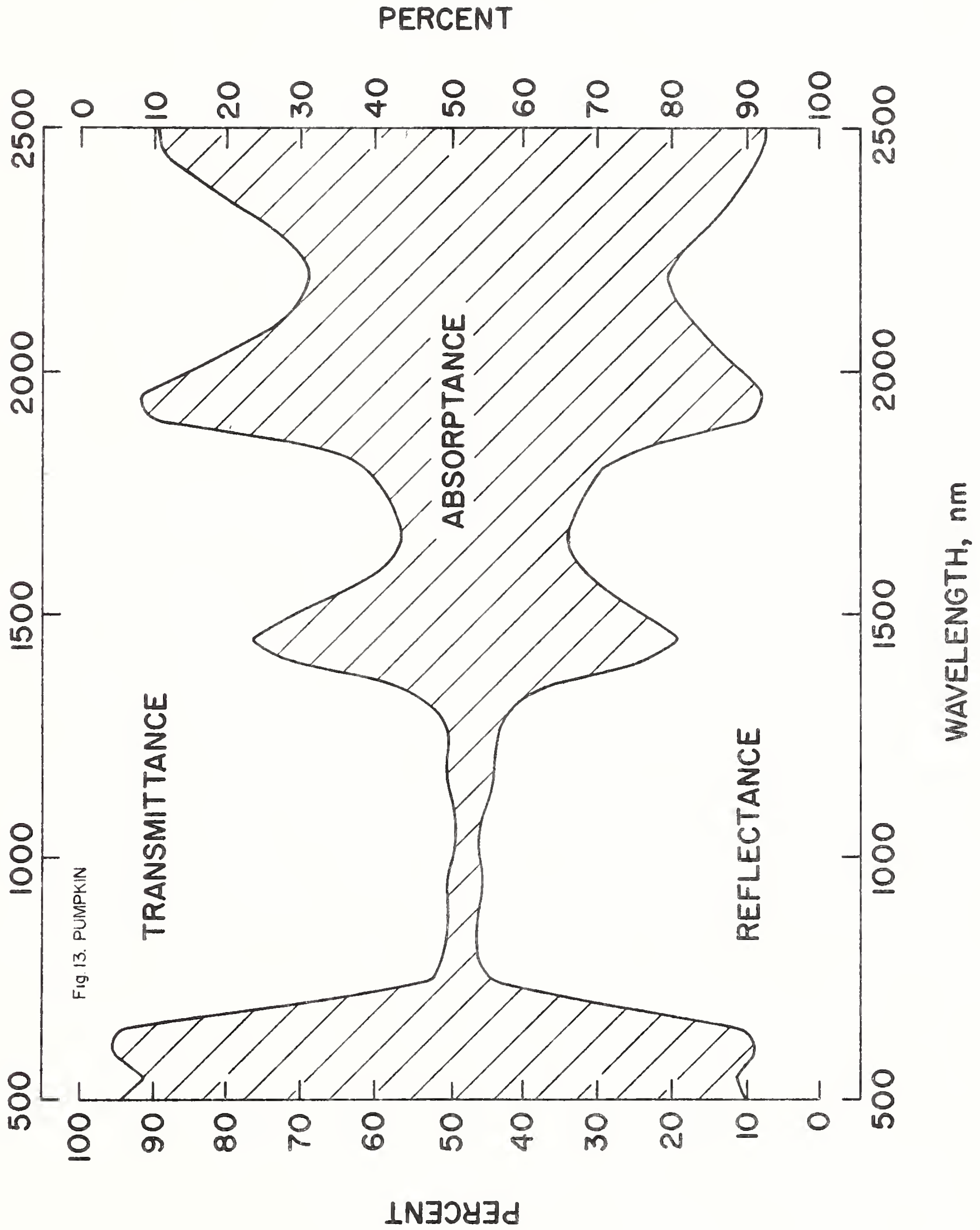


Fig.13. PUMPKIN

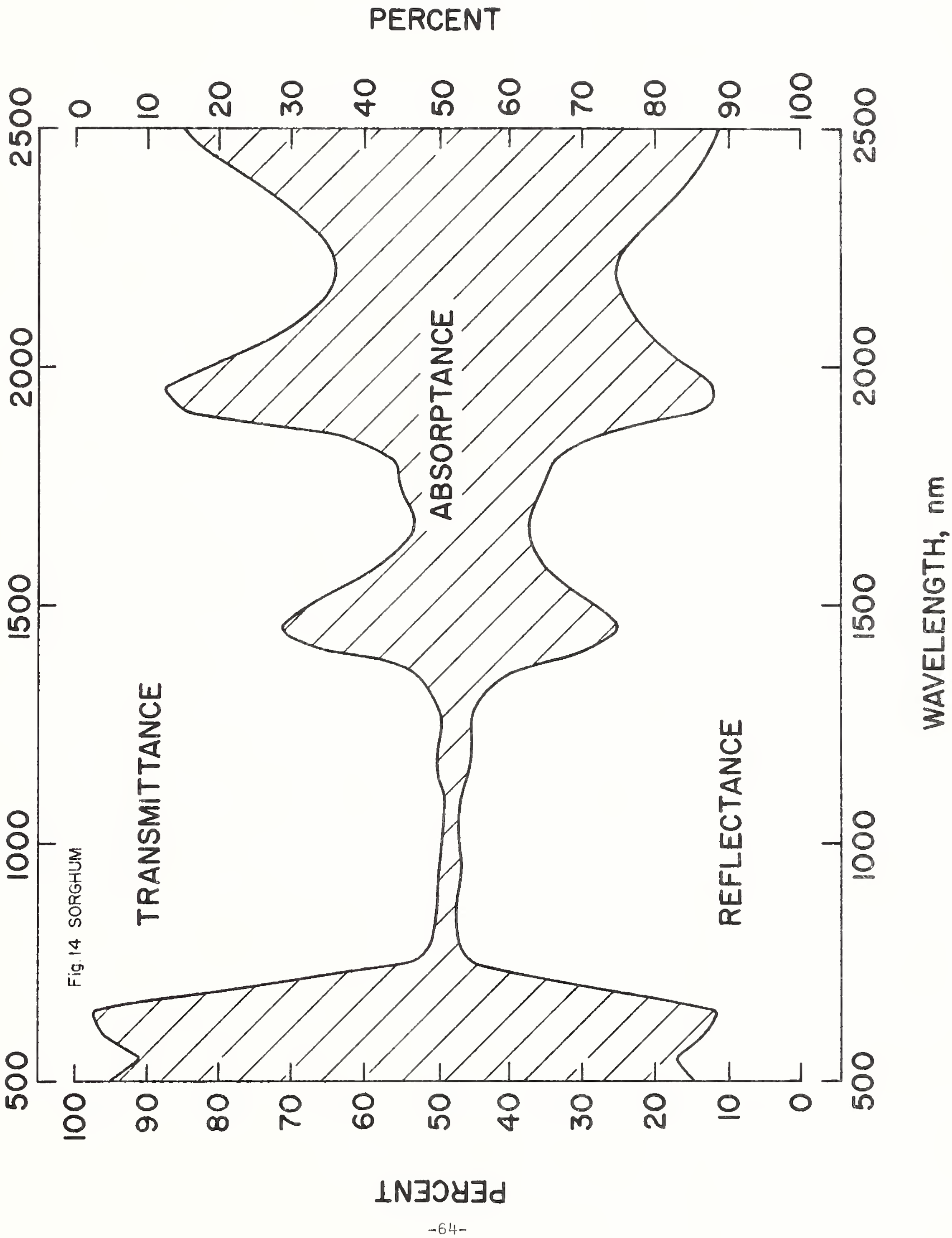


Fig. 14 SORGHUM

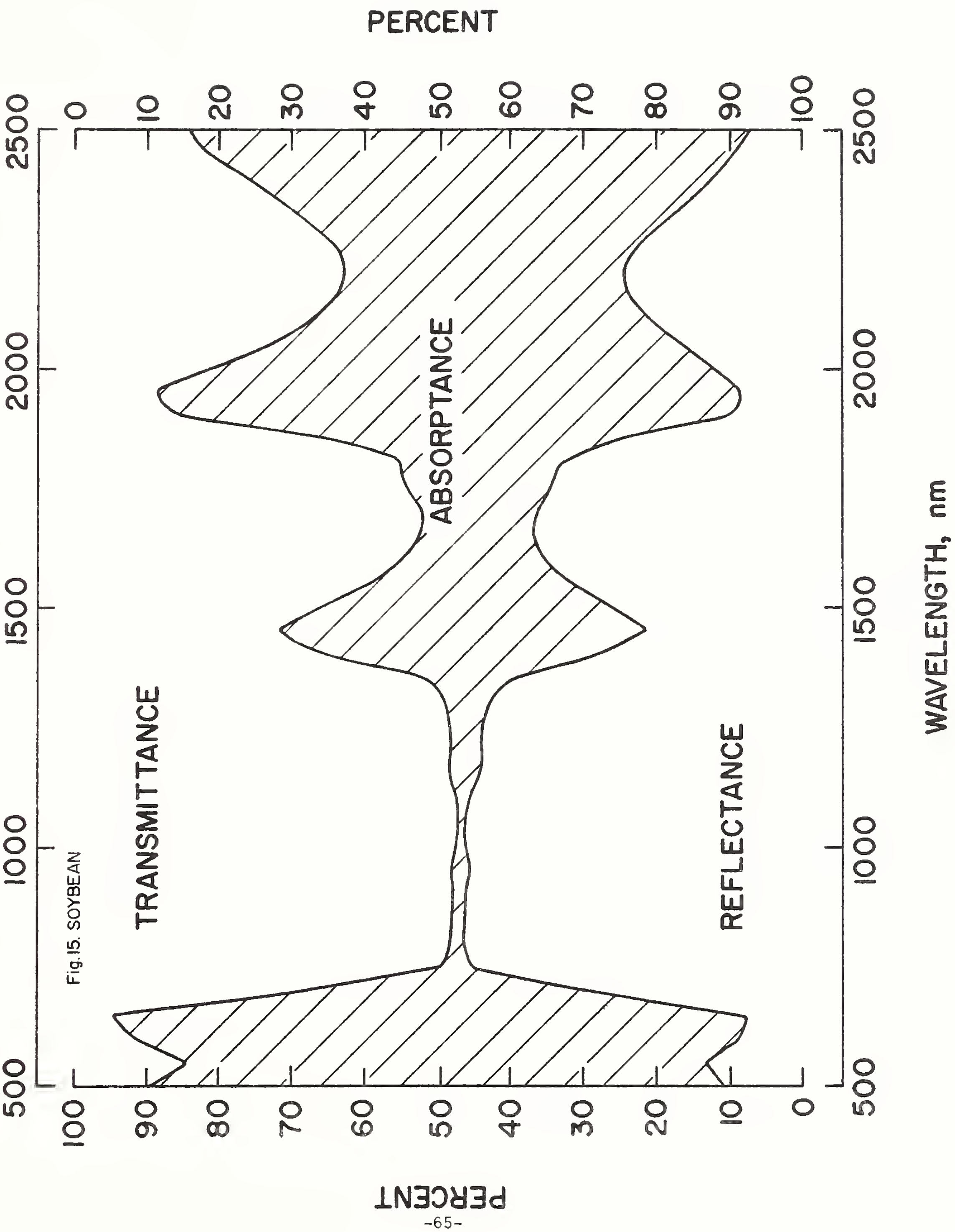


Fig.15. SOYBEAN

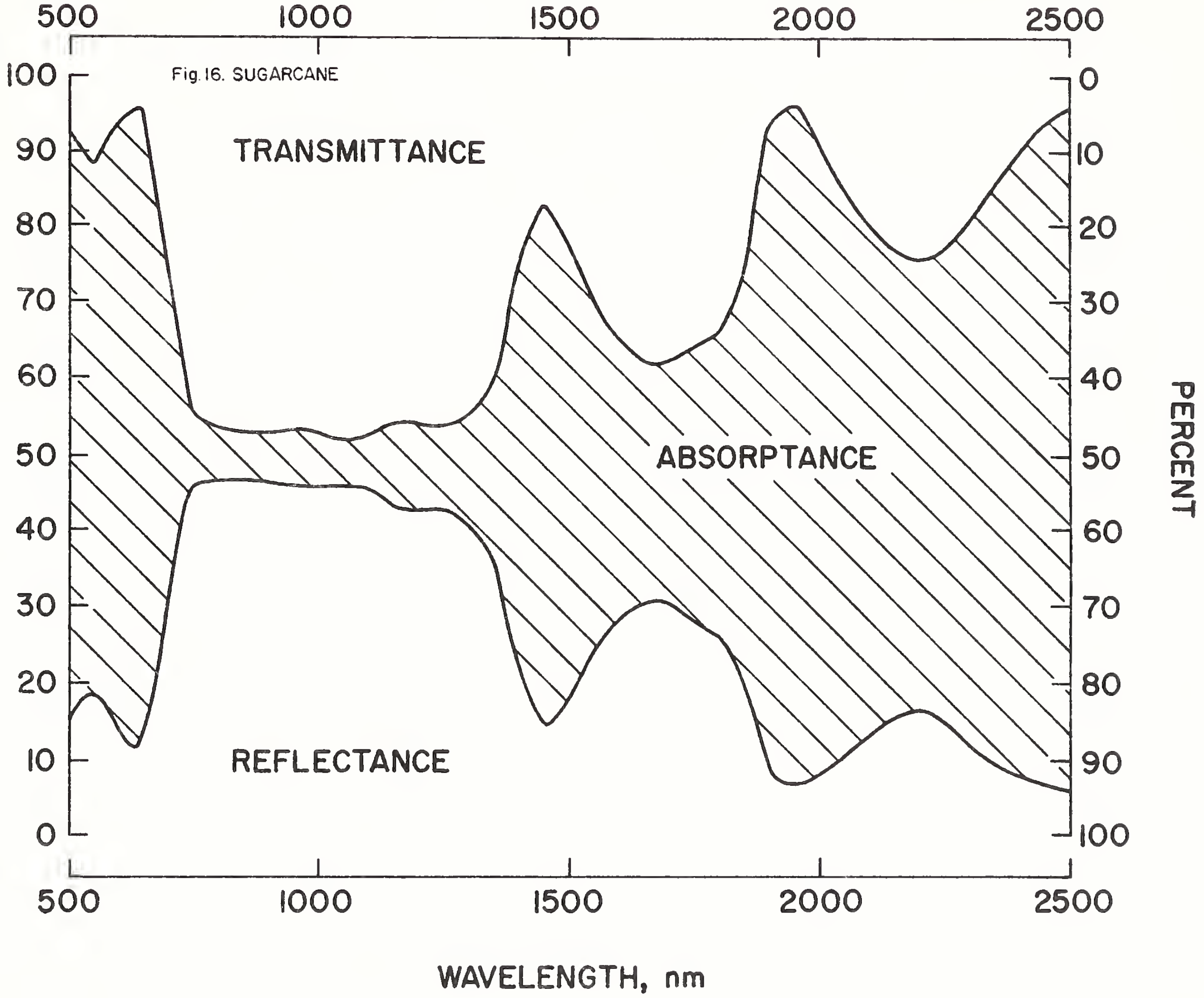


Fig. 16. SUGARCANE

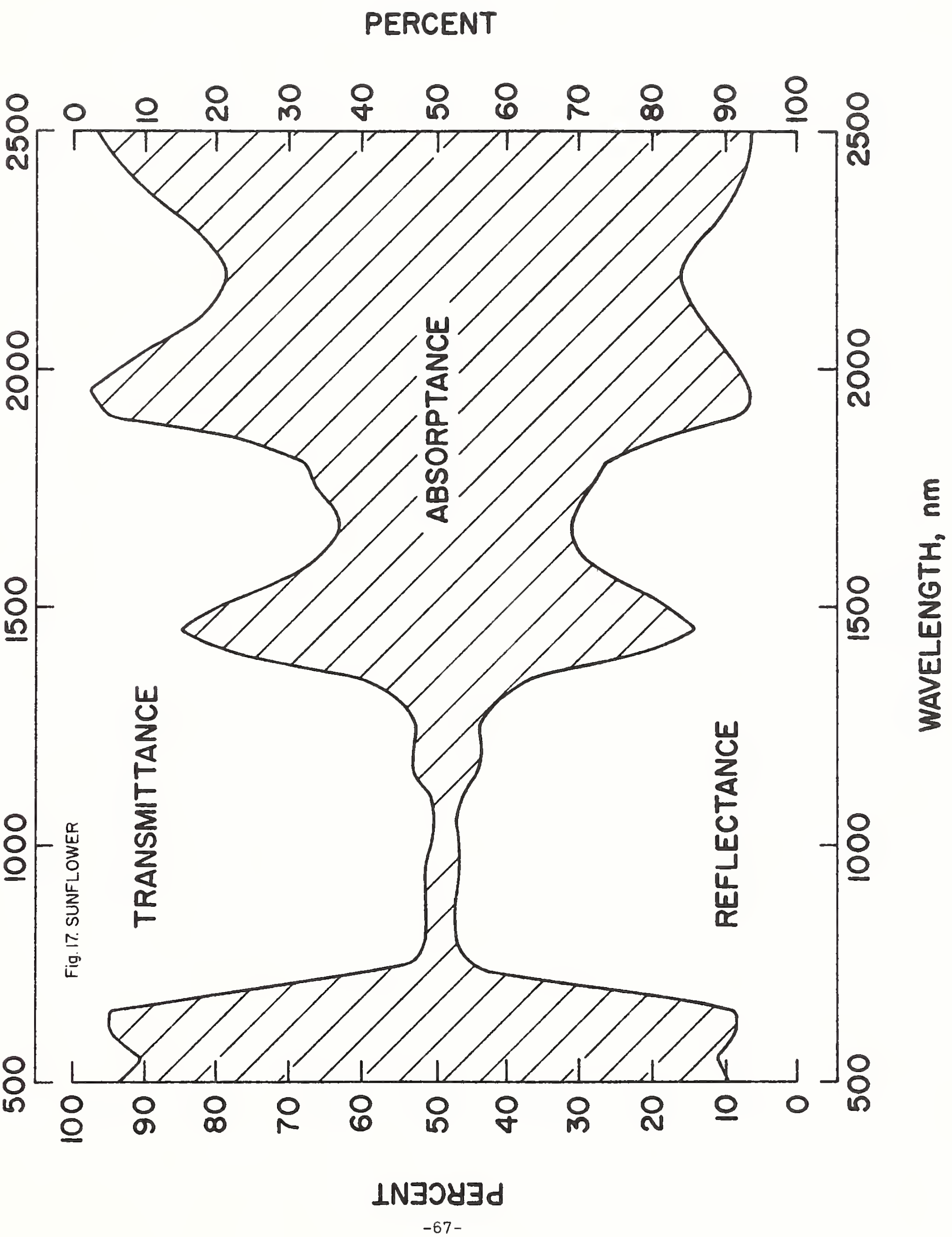


Fig. 17. SUNFLOWER

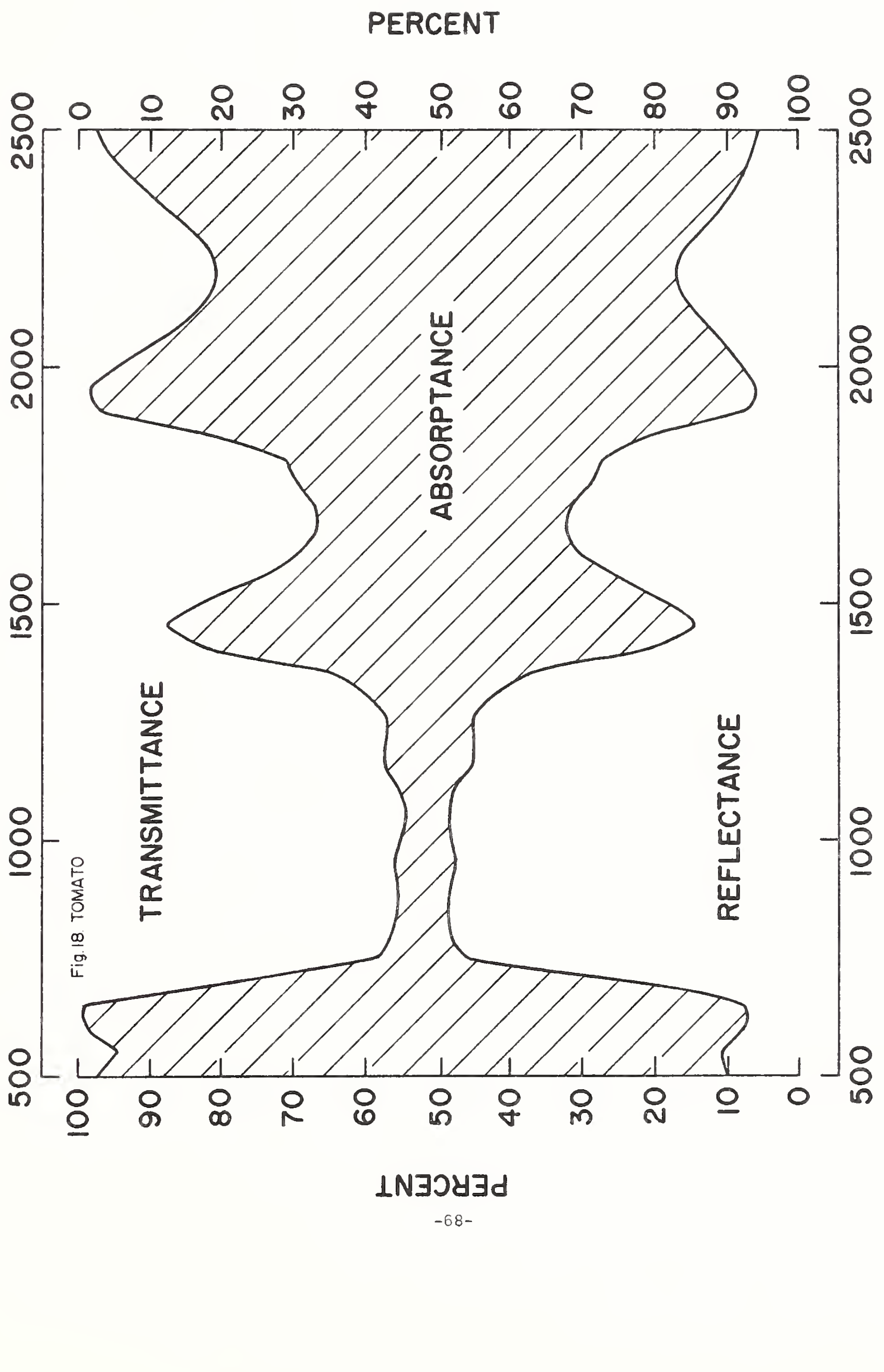


Fig. 18 TOMATO

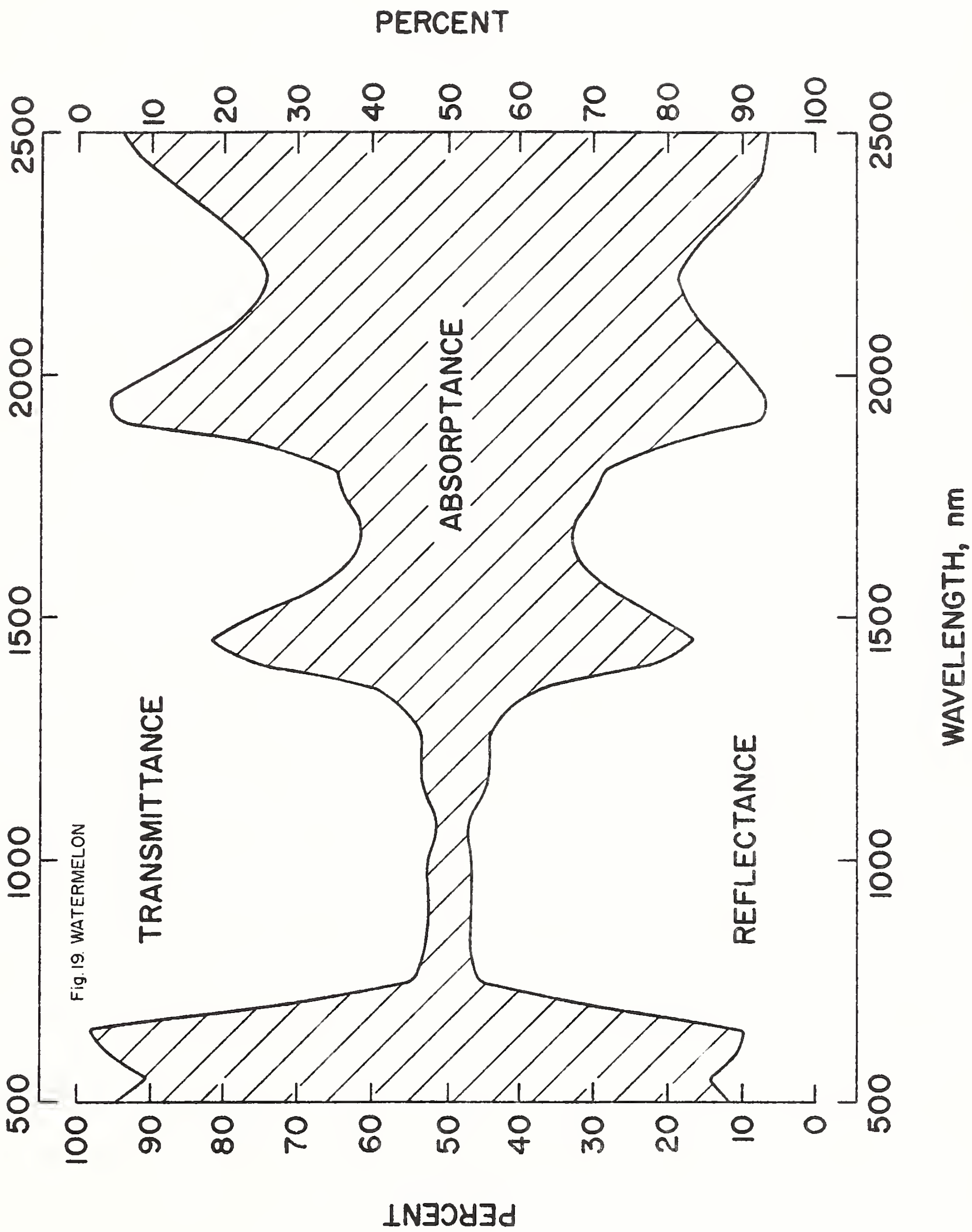
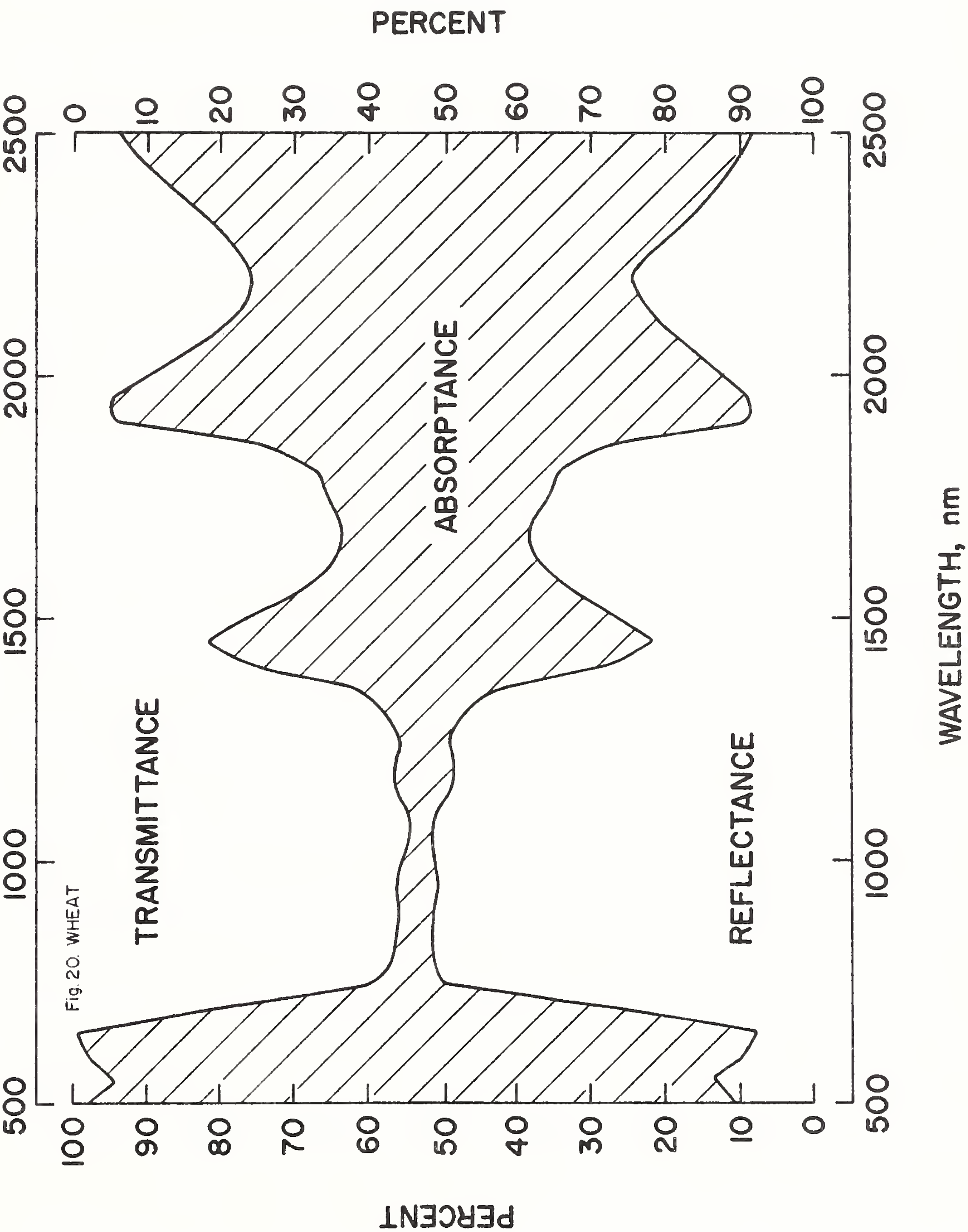


Fig. 19. WATERMELON


PERCENT
0
10
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80
90
100
TRANSMITTANCE
ABSORPTANCE
REFLECTANCE
500
1000
1500
2000
2500
WAVELENGTH, nm
PERCENT
100
90
80
70
60
50
40
30
20
10
0

Fig. 20. WHEAT

Appendix Table 1. Average percent reflectances of top leaf surfaces of 10 leaves for each of 20 crops for 41 WL (nm) over the 500- to 2500-nm WLI.

Crop	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150
Avocado	8.2	8.9	6.8	7.2	26.6	47.9	50.4	50.3	50.1	49.4	49.7	49.7	49.3	47.1
Bean	15.2	18.5	12.0	10.7	37.3	55.7	56.9	56.9	56.5	55.8	56.2	56.6	56.0	53.6
Cantaloupe	11.6	12.7	10.0	9.9	28.6	46.1	47.7	47.7	47.5	46.8	47.3	47.6	47.0	44.6
Corn	12.7	16.2	12.0	9.3	24.8	45.4	46.3	46.4	46.2	45.5	45.7	46.0	45.5	43.3
Cotton	9.8	11.8	8.0	7.7	28.6	45.8	47.2	47.2	46.9	46.2	46.6	47.0	46.4	44.2
Lettuce	27.6	30.3	26.8	23.6	33.7	37.6	37.6	37.5	36.7	34.6	35.3	36.3	35.0	30.3
Okra	10.8	12.9	9.5	9.2	29.0	47.2	49.0	49.2	49.0	48.4	48.7	49.0	48.5	46.6
Onion	10.1	11.6	8.5	8.1	25.0	39.4	40.5	40.4	39.6	37.7	38.5	39.4	38.2	33.3
Orange	8.9	10.2	7.2	7.1	28.9	53.2	55.8	55.9	55.7	55.2	55.6	55.7	55.4	53.1
Peach	9.6	10.9	8.3	8.6	29.1	47.7	49.5	49.5	49.3	49.0	49.3	49.4	49.1	47.7
Pepper	12.8	16.8	11.0	9.3	32.8	50.5	51.6	51.6	51.4	50.7	51.0	51.4	40.8	48.5
Pigweed	10.9	12.4	9.3	9.0	26.6	43.9	45.7	45.5	45.4	44.8	45.1	45.1	44.6	42.8
Pumpkin	10.2	11.8	8.9	10.6	29.1	44.9	46.4	46.3	46.2	45.8	46.7	46.2	45.7	44.2
Sorghum	15.0	17.2	13.3	11.3	28.2	45.8	47.3	47.4	47.3	46.9	47.0	47.0	46.8	45.5
Soybean	10.9	13.1	8.7	7.9	28.8	45.6	46.6	46.5	46.3	45.9	46.0	46.2	45.8	44.5
Sugarcane	15.9	18.6	13.4	11.4	29.9	45.8	46.9	46.8	46.4	45.6	45.7	46.0	45.4	42.9
Sunflower	9.6	11.0	8.4	8.5	27.5	45.4	47.3	47.3	47.1	46.5	46.9	47.2	46.6	44.1
Tomato	10.0	11.1	8.6	8.6	25.9	46.6	48.4	48.6	48.5	47.8	48.3	48.6	48.0	45.4
Watermelon	11.9	14.4	10.7	9.9	30.4	45.6	46.8	47.0	47.0	46.3	46.8	47.2	46.6	44.5
Wheat	10.3	13.4	9.6	7.7	27.3	50.2	51.5	51.7	51.4	51.0	51.2	51.5	51.0	48.9

Appendix Table 1. Continued

Crop	1200	1250	1300	1350	1400	1450	1500	1550	1600	1650	1700	1750	1800	1850
Avocado	46.8	47.1	45.2	41.0	26.3	19.2	23.1	29.0	32.5	34.1	33.2	31.2	30.3	23.1
Bean	53.5	53.6	50.8	44.9	25.6	18.5	24.6	33.1	38.4	40.9	40.6	37.5	35.2	24.2
Cantaloupe	44.3	44.5	41.9	36.7	20.6	14.8	19.1	25.5	29.9	32.0	31.5	28.9	27.4	19.4
Corn	43.2	43.5	41.8	38.3	23.4	16.8	21.0	27.1	31.0	32.9	32.6	30.1	28.8	23.1
Cotton	44.0	44.2	42.0	37.5	21.7	15.2	19.6	26.2	30.4	32.3	31.9	29.4	27.9	19.9
Lettuce	29.6	29.8	26.4	21.4	11.8	9.1	10.4	13.0	15.4	16.8	16.8	15.0	13.8	10.6
Okra	46.2	46.4	44.5	40.4	25.6	18.1	22.3	28.8	33.0	35.0	34.5	32.3	30.8	23.0
Onion	32.5	32.9	29.0	23.0	10.3	6.8	8.4	12.0	15.1	17.2	17.0	14.6	13.1	9.4
Orange	52.8	53.0	51.2	47.1	31.2	22.3	26.6	33.3	37.6	39.8	39.0	36.6	35.4	27.8
Peach	47.7	47.8	46.5	43.0	30.3	24.3	28.8	34.3	37.5	38.9	38.0	36.4	35.6	27.4
Pepper	48.4	48.6	46.4	41.7	25.0	17.6	22.6	30.0	34.7	36.9	36.6	33.9	32.2	23.4
Pigweed	42.5	42.6	40.6	36.2	21.5	15.6	19.9	26.1	30.0	31.8	31.3	29.1	27.6	19.5
Pumpkin	44.0	44.0	42.1	37.4	24.6	19.0	23.6	29.2	32.6	34.6	33.1	31.3	29.5	21.6
Sorghum	45.3	45.4	44.3	41.7	30.9	24.7	28.2	33.2	36.1	37.4	36.9	35.3	34.2	28.2
Soybean	44.5	44.4	43.1	40.1	27.7	21.8	26.1	31.9	35.2	36.6	36.3	34.5	33.3	25.5
Sugarcane	42.6	42.7	40.5	35.9	20.7	14.4	18.3	24.2	28.0	30.4	30.0	27.5	25.9	18.8
Sunflower	44.0	44.2	41.7	36.4	20.4	14.3	18.4	24.9	29.3	31.3	30.5	28.1	26.6	18.9
Tomato	45.2	45.4	42.7	37.3	20.5	14.4	18.9	25.6	30.0	32.1	31.7	28.9	27.3	19.1
Watermelon	44.4	44.5	42.2	37.5	22.0	16.6	21.2	27.4	31.2	33.0	32.4	29.9	28.7	20.5
Wheat	48.8	49.2	47.2	43.5	27.7	21.7	26.5	32.7	36.4	38.2	37.4	35.2	34.3	27.3

Appendix Table 1. Continued.

Crop	1900	1950	2000	2050	2100	2150	2200	2250	2300	2350	2400	2450	2500
Avocado	9.7	7.5	10.2	13.2	15.7	18.1	19.5	17.4	14.2	11.6	9.5	7.8	7.0
Bean	8.0	6.0	9.4	14.1	18.9	22.6	24.0	21.5	17.2	12.8	9.5	7.2	5.9
Cantaloupe	8.1	6.9	8.6	11.1	14.2	16.5	17.5	15.7	12.6	9.9	8.0	6.6	6.0
Corn	7.9	7.2	9.7	12.6	15.8	18.3	19.8	17.6	14.4	11.6	9.3	7.5	6.7
Cotton	7.6	6.0	7.9	10.8	14.1	16.7	16.8	15.8	12.5	9.8	7.5	6.0	5.3
Lettuce	6.2	5.6	6.4	7.4	8.4	9.2	9.4	8.8	7.7	6.6	5.8	5.2	4.9
Okra	9.4	7.0	9.4	12.8	16.3	19.0	20.2	18.3	14.9	11.8	9.3	7.3	6.5
Onion	4.9	4.4	4.9	5.6	6.6	7.6	8.0	7.4	6.3	5.4	4.8	4.6	4.5
Orange	11.4	8.6	12.0	15.8	19.2	22.1	23.6	21.2	17.4	14.1	11.1	9.0	7.8
Peach	12.5	10.5	14.4	18.3	21.6	24.3	25.7	23.1	19.3	16.0	13.2	10.7	9.5
Pepper	8.5	6.6	9.4	13.2	17.1	20.2	21.5	19.3	15.4	11.7	8.9	6.8	5.7
Pigweed	7.7	5.8	8.0	11.0	14.3	16.8	17.8	15.9	12.9	9.9	7.6	5.9	5.1
Pumpkin	9.0	7.1	10.6	14.0	17.2	19.5	20.9	18.2	14.9	12.1	9.6	7.6	7.0
Sorghum	14.1	12.0	15.6	19.1	22.1	24.5	25.8	23.7	20.4	17.4	14.7	12.4	11.3
Soybean	10.2	8.1	12.1	16.6	20.6	23.5	24.8	22.7	19.1	15.4	12.1	9.5	8.2
Sugarcane	7.6	6.2	8.2	10.5	13.1	15.5	16.4	14.5	11.8	9.5	7.8	6.5	6.0
Sunflower	8.0	6.5	8.1	10.4	13.2	15.4	16.2	14.4	11.6	9.3	7.6	6.5	6.0
Tomato	7.3	6.0	7.9	10.7	13.7	16.3	17.3	15.3	12.2	9.5	7.4	6.0	5.4
Watermelon	8.0	6.9	9.1	12.1	15.3	17.7	18.8	16.8	13.5	10.8	8.5	6.9	6.2
Wheat	9.7	9.0	12.8	16.6	20.2	22.6	24.4	21.7	18.2	15.0	12.2	9.7	8.5

Appendix Table 2. Average percent transmittances of top leaf surfaces of 10 leaves for each of 20 crops for 41 WL (nm) over the 500- to 2500-nm WLI.

Crop	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150
Avocado	2.3	4.1	1.4	3.1	24.9	42.4	44.8	45.4	45.5	45.5	46.1	46.6	46.3	45.0
Bean	6.9	10.9	5.5	3.6	26.6	40.9	42.0	42.2	42.0	41.5	42.2	42.4	41.9	39.9
Cantaloupe	4.9	8.7	3.9	2.4	27.5	46.3	48.1	48.6	48.6	48.0	48.8	49.5	49.0	46.5
Corn	3.7	9.8	3.7	0.7	22.6	48.9	50.5	50.9	51.1	50.7	51.2	51.7	51.6	49.7
Cotton	8.1	13.1	7.0	4.2	30.6	47.8	49.1	49.4	49.3	39.0	49.4	49.9	49.6	47.8
Lettuce	38.4	44.3	39.5	34.0	49.5	55.3	55.6	55.5	54.8	52.6	53.7	54.9	53.7	48.2
Okra	5.9	14.8	5.8	4.1	27.1	44.6	46.4	46.7	46.9	46.7	47.3	47.8	47.6	46.0
Onion	11.7	18.8	10.8	6.6	35.8	54.3	55.7	55.7	55.0	52.9	54.0	55.4	54.1	48.2
Orange	0.7	1.9	0.5	0.5	17.6	36.0	38.2	38.6	38.6	38.4	38.9	39.5	39.3	37.7
Peach	3.5	6.2	2.6	2.8	27.1	45.5	47.3	47.6	47.7	47.6	47.9	48.3	48.1	47.1
Pepper	6.9	12.6	6.4	3.1	28.4	44.8	46.2	46.5	46.4	46.0	46.5	47.0	46.7	44.9
Pigweed	5.4	9.5	3.7	2.7	28.6	49.2	51.6	52.0	52.0	51.9	52.4	52.9	52.6	51.0
Pumpkin	5.6	8.8	4.3	5.6	30.0	47.1	48.9	49.4	49.6	49.5	50.1	50.6	50.4	49.1
Sorghum	5.0	9.0	4.2	2.1	24.4	46.7	49.1	49.6	49.8	49.9	50.3	50.8	50.7	49.8
Soybean	10.0	15.6	8.7	5.4	32.5	50.0	51.4	51.8	51.9	51.8	52.2	52.6	52.4	51.4
Sugarcane	7.5	12.2	6.9	4.1	26.7	45.0	46.9	47.2	47.3	46.9	47.6	48.1	47.9	46.0
Sunflower	6.3	9.1	5.7	5.1	27.8	46.4	48.4	48.8	48.8	48.4	49.1	49.7	49.2	46.8
Tomato	2.6	5.5	1.5	0.9	23.6	41.9	43.8	44.3	44.4	44.0	44.7	45.3	44.9	42.6
Watermelon	5.2	9.6	4.3	2.0	28.7	45.2	46.6	47.1	47.4	47.2	47.9	48.5	48.2	46.3
Wheat	1.9	5.8	2.1	0.7	20.3	41.8	43.4	43.9	44.1	43.9	44.6	45.2	45.1	43.4

Appendix Table 2. Continued

Crop	1200	1250	1300	1350	1400	1450	1500	1550	1600	1650	1700	1750	1800	1850
Avocado	45.1	45.6	44.0	39.4	26.1	20.5	25.6	32.0	35.8	37.6	37.0	35.4	34.1	25.1
Bean	40.0	40.2	38.1	33.5	17.3	11.8	17.3	24.9	29.6	32.2	32.2	29.5	27.9	18.5
Cantaloupe	46.6	47.0	44.5	39.2	20.6	14.6	19.7	28.2	33.7	36.6	36.5	33.6	32.0	21.8
Corn	49.8	50.5	49.0	45.9	28.8	20.5	26.8	35.1	40.2	43.0	43.1	40.6	39.6	32.0
Cotton	47.9	48.3	46.6	42.7	26.7	19.6	25.4	33.2	38.0	40.4	40.3	38.1	37.0	27.1
Lettuce	47.4	48.0	43.7	35.9	14.6	6.2	11.1	19.9	26.6	30.5	31.0	27.0	24.4	15.2
Okra	46.1	46.5	45.0	41.5	26.8	19.3	24.5	32.0	36.6	39.2	39.1	37.0	35.9	27.3
Onion	47.4	48.1	43.4	35.1	12.5	4.1	8.7	17.5	24.3	28.4	28.8	24.7	22.0	13.1
Orange	37.6	38.2	36.9	33.7	20.1	13.0	17.2	23.5	27.6	30.0	29.6	27.6	26.9	20.2
Peach	47.3	47.7	46.7	43.9	31.5	26.2	31.3	37.4	40.9	42.8	42.3	40.9	40.6	31.7
Pepper	45.0	45.4	43.7	39.8	23.9	16.9	22.7	30.4	35.3	37.8	37.8	35.4	34.0	25.0
Pigweed	51.2	51.6	49.9	45.8	29.9	23.1	29.1	37.1	41.9	44.5	44.4	42.2	41.0	30.3
Pumpkin	49.3	49.7	48.2	43.7	29.5	23.8	29.7	36.8	41.2	43.5	43.1	41.1	39.5	29.2
Sorghum	50.0	50.4	49.6	47.3	35.1	28.2	33.2	39.9	44.0	46.2	46.3	44.8	44.1	36.6
Soybean	51.6	51.9	50.8	48.0	34.9	28.7	34.3	41.3	45.3	47.4	47.5	45.8	44.8	35.5
Sugarcane	46.0	46.5	44.9	40.8	24.6	17.3	23.0	30.7	35.7	38.5	38.4	36.0	34.8	25.1
Sunflower	46.8	47.3	45.1	40.0	22.2	15.0	21.0	29.1	34.4	37.0	36.6	34.0	32.7	22.5
Tomato	42.6	43.0	40.7	35.9	18.6	12.3	17.9	25.7	30.8	33.4	33.3	30.5	29.1	19.6
Watermelon	46.5	47.0	45.0	40.7	24.1	18.3	24.3	31.8	36.5	38.8	38.6	36.2	35.3	25.3
Wheat	43.6	44.2	42.8	39.7	24.3	18.5	23.9	30.7	34.7	36.8	36.3	34.3	33.7	26.7

Appendix Table 2. Continued.

Crop	1900	1950	2000	2050	2100	2150	2200	2250	2300	2350	2400	2450	2500
Avocado	8.8	6.7	12.3	17.3	21.2	24.0	25.2	23.3	19.8	16.2	12.1	9.8	6.9
Bean	3.7	1.9	5.4	10.3	15.3	18.6	19.7	18.4	15.2	11.3	7.8	4.9	3.5
Cantaloupe	4.2	2.1	6.0	11.5	16.9	20.5	21.8	20.1	16.4	12.1	8.1	5.0	3.4
Corn	6.5	5.0	11.8	18.6	24.6	28.5	30.3	28.3	24.4	19.9	14.8	9.7	7.0
Cotton	7.4	4.5	10.2	16.8	22.6	26.2	27.7	26.1	22.5	17.9	12.9	8.8	6.6
Lettuce	2.1	0.5	1.7	4.5	8.8	12.2	13.5	12.2	9.0	5.6	2.9	1.4	0.8
Okra	8.6	5.2	10.7	16.8	22.2	25.7	27.1	25.7	22.2	18.1	13.6	9.7	7.5
Onion	1.2	0.5	0.6	2.5	6.0	9.0	10.2	8.8	6.0	3.1	1.2	0.5	0.5
Orange	5.3	2.6	6.2	10.3	14.1	16.8	18.1	16.5	13.6	10.7	7.8	5.1	3.8
Peach	12.6	10.4	17.3	23.4	28.1	31.2	32.5	30.6	27.2	23.6	19.1	14.7	12.2
Pepper	6.3	3.8	8.9	15.0	20.5	24.2	25.6	24.2	20.8	16.4	11.9	8.1	6.0
Pigweed	9.9	6.9	13.5	20.7	26.8	30.7	32.2	30.6	26.9	22.2	17.0	12.4	9.6
Pumpkin	10.2	8.3	14.9	21.4	26.8	30.1	31.3	29.4	25.8	21.5	16.7	11.9	10.2
Sorghum	15.4	12.2	19.9	26.7	31.9	35.3	36.9	35.4	32.1	28.2	23.6	18.4	15.6
Soybean	14.6	11.7	19.3	26.7	32.7	36.3	37.7	36.3	33.0	28.6	23.5	18.5	15.8
Sugarcane	6.7	4.0	9.3	15.1	20.0	23.7	25.0	23.0	19.3	15.1	10.8	7.0	4.9
Sunflower	6.0	2.3	6.5	11.9	17.1	20.5	21.6	19.7	16.1	12.1	8.2	5.0	3.3
Tomato	3.7	1.8	5.4	10.2	15.2	18.6	19.8	18.2	14.8	10.8	7.2	4.3	3.0
Watermelon	6.1	4.6	10.1	16.1	21.3	24.7	26.1	24.4	20.7	16.6	12.2	8.2	6.3
Wheat	6.0	5.2	10.7	15.9	20.4	23.3	24.7	22.8	19.6	16.2	12.3	8.6	6.5

Appendix Table 3. Average percent absorptances for top leaf surfaces of 10 leaves for each of 20 crops for 41 WL (nm) over the 500- to 2500-nm WLI.

Crop	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150
Avocado	89.5	87.0	91.8	89.1	48.5	9.6	4.7	4.2	4.3	5.0	4.2	3.6	4.4	7.9
Bean	77.9	70.6	82.4	85.7	36.1	3.4	1.2	1.0	11.5	2.7	1.8	1.0	2.1	6.5
Cantaloupe	83.5	78.6	86.0	87.7	43.8	7.6	4.2	3.7	3.9	5.2	3.9	2.9	4.0	9.0
Corn	83.6	74.0	84.3	90.0	52.6	5.7	3.2	2.7	2.7	3.9	3.2	2.3	2.8	7.0
Cotton	82.1	75.1	85.0	88.1	40.8	6.4	3.7	3.4	3.8	4.8	4.0	3.2	4.1	7.9
Lettuce	34.0	25.4	33.8	42.4	16.8	7.1	6.8	7.0	8.5	12.8	11.0	8.8	11.3	21.5
Okra	83.3	72.2	84.7	86.7	43.8	8.2	4.5	4.1	4.1	4.9	4.0	3.2	4.0	7.4
Onion	78.2	69.7	80.7	85.3	39.3	6.2	3.8	4.0	5.4	9.4	7.5	5.2	7.7	18.4
Orange	90.4	87.9	92.3	92.4	53.5	10.8	6.0	5.6	5.7	6.4	5.5	4.8	5.3	9.2
Peach	86.8	82.9	89.1	88.5	43.8	6.8	3.2	2.9	3.0	3.4	2.8	2.3	2.8	5.2
Pepper	80.3	70.6	82.6	87.5	38.8	4.7	2.2	1.9	2.2	3.3	2.4	1.6	2.5	6.5
Pigweed	83.7	78.2	87.0	88.3	44.9	6.9	2.7	2.5	2.6	3.4	2.5	2.0	2.7	6.2
Pumpkin	84.2	79.5	86.8	83.8	40.9	8.0	4.7	4.3	4.2	4.6	3.2	3.1	4.0	6.8
Sorghum	80.1	73.8	82.6	86.6	47.4	7.5	3.6	3.0	2.8	3.3	2.7	2.2	2.5	4.7
Soybean	79.1	71.3	82.7	86.6	38.7	4.4	2.0	1.8	1.8	2.3	1.8	1.2	1.8	4.1
Sugarcane	76.6	69.2	79.7	84.5	43.4	9.2	6.2	6.0	6.3	7.5	6.7	5.9	6.7	11.1
Sunflower	84.1	79.9	85.9	86.4	44.8	8.2	4.3	3.8	4.1	5.1	4.1	3.2	4.3	9.1
Tomato	87.4	83.6	90.0	90.4	50.6	11.5	7.8	7.1	7.1	8.2	7.0	6.0	7.0	12.1
Watermelon	82.9	75.9	85.0	88.1	40.9	9.2	6.5	5.9	5.7	6.5	5.3	4.4	5.3	9.2
Wheat	87.8	80.7	88.3	91.6	52.5	8.0	5.1	4.4	4.4	5.1	4.2	3.3	3.8	7.7

Appendix Table 3. Continued.

Crop	1200	1250	1300	1350	1400	1450	1500	1550	1600	1650	1700	1750	1800	1850
Avocado	8.1	7.3	10.8	19.5	47.6	60.4	51.3	39.0	31.7	28.3	29.7	33.4	35.6	51.8
Bean	6.5	6.2	11.1	21.6	57.2	69.8	58.1	42.1	32.0	26.9	27.3	33.0	36.8	57.3
Cantaloupe	9.1	8.5	13.5	24.1	58.8	70.6	61.3	46.3	36.4	31.4	35.0	37.6	40.6	58.8
Corn	7.1	6.0	9.3	15.8	47.8	62.7	52.3	37.7	28.8	24.1	24.4	29.4	31.6	44.9
Cotton	8.0	7.5	11.4	19.9	51.6	65.1	55.0	40.6	31.7	27.2	27.8	32.5	35.1	52.9
Lettuce	23.0	22.2	30.0	42.7	73.6	84.7	78.5	67.1	58.1	52.7	52.2	58.0	61.8	74.2
Okra	7.7	7.0	10.5	18.1	47.6	62.6	53.2	39.2	30.4	25.8	26.5	30.7	33.2	49.7
Onion	20.0	19.0	27.6	41.9	77.2	89.1	82.9	70.5	60.6	54.4	54.2	60.7	64.9	77.5
Orange	9.6	8.8	11.9	19.2	48.6	64.6	56.2	43.2	34.8	30.2	31.4	35.9	17.7	51.9
Peach	5.0	4.5	6.8	13.1	38.3	49.5	39.9	28.1	21.6	18.3	19.6	22.6	25.8	40.9
Pepper	6.6	6.0	10.0	18.5	51.1	65.4	54.7	39.5	30.1	25.3	25.6	30.8	33.8	51.6
Pigweed	6.3	5.8	9.5	18.0	48.6	61.3	51.0	36.8	28.1	23.7	24.3	28.8	31.4	50.1
Pumpkin	6.7	6.4	9.8	18.8	45.9	57.2	46.8	33.9	26.1	22.0	23.8	27.6	31.0	49.2
Sorghum	4.8	4.2	6.2	11.0	33.9	47.1	38.6	26.9	19.9	16.4	16.8	20.0	21.6	35.1
Soybean	4.0	3.7	6.1	11.9	37.4	49.5	39.7	26.9	19.5	15.9	16.2	19.8	21.8	38.9
Sugarcane	11.4	10.7	14.6	23.3	54.7	68.2	58.8	45.0	36.0	31.1	31.5	36.5	39.3	55.6
Sunflower	9.2	8.6	13.3	23.6	57.3	70.7	60.6	46.0	36.4	31.7	32.9	37.9	40.7	58.6
Tomato	12.1	11.5	16.6	26.9	60.9	73.3	63.2	48.7	39.2	34.5	35.1	40.6	43.6	61.3
Watermelon	9.2	8.6	12.8	21.8	54.0	65.1	54.5	40.8	32.3	28.2	29.1	33.9	36.0	54.2
Wheat	7.6	6.6	10.0	16.8	48.0	59.7	49.6	36.7	29.0	25.1	26.3	30.6	32.0	45.8

Appendix Table 3. Continued.

Crop	1900	1950	2000	2050	2100	2150	2200	2250	2300	2350	2400	2450	2500
Avocado	81.5	85.7	77.5	69.4	63.1	57.9	55.4	59.3	66.0	72.2	78.4	82.3	86.1
Beans	88.3	92.1	85.2	75.5	65.7	58.8	56.3	60.1	67.6	75.9	82.8	89.0	90.6
Cantaloupe	87.8	91.1	85.4	77.4	68.9	63.0	60.7	64.2	71.0	78.0	83.9	88.4	90.6
Corn	85.6	87.8	78.5	68.8	59.6	53.2	50.0	54.1	61.2	68.6	75.9	82.8	86.3
Cotton	85.0	89.5	82.0	72.4	63.3	57.1	63.3	42.0	65.0	72.3	79.6	85.2	88.1
Lettuce	91.7	93.9	91.9	88.1	82.9	78.6	77.1	79.1	83.3	87.8	91.3	93.4	94.3
Okra	82.1	87.8	79.9	70.4	61.5	55.3	52.6	56.0	62.8	70.1	77.2	83.0	86.0
Onion	93.9	95.1	94.5	91.9	87.4	83.3	81.8	83.8	87.7	91.5	94.1	94.9	95.0
Orange	83.3	88.8	81.8	73.9	66.8	61.0	58.3	62.3	69.0	75.2	81.2	85.9	88.4
Peach	74.9	79.2	68.4	58.3	50.3	44.5	41.9	46.4	53.5	60.4	67.8	74.6	78.3
Pepper	85.1	89.5	81.7	71.8	62.4	55.6	52.9	56.5	63.8	71.8	79.2	85.0	88.2
Pigweed	82.4	87.4	78.6	68.3	58.9	52.5	50.1	53.5	60.2	67.9	75.4	81.7	85.3
Pumpkin	80.8	84.0	74.5	64.5	56.0	50.4	47.9	52.4	59.3	66.4	73.6	80.5	82.7
Sorghum	70.5	75.9	64.5	54.2	46.0	40.2	37.4	41.0	47.5	54.4	61.8	69.2	73.2
Soybean	75.3	80.2	68.6	56.7	46.7	40.2	37.6	41.0	47.9	56.0	64.4	72.0	76.1
Sugarcane	85.7	89.8	82.5	74.3	66.9	60.8	58.6	62.3	68.9	75.4	81.4	86.5	89.1
Sunflower	87.1	91.2	85.4	77.6	69.7	64.1	62.2	65.9	72.3	78.6	83.6	88.5	90.7
Tomato	89.0	92.2	86.7	79.1	71.1	65.2	63.0	66.4	73.0	79.7	85.4	89.6	91.6
Watermelon	85.9	88.5	80.8	71.8	63.4	57.6	55.1	58.9	65.8	72.6	79.3	84.9	87.5
Wheat	84.2	85.8	76.5	67.5	59.4	54.1	50.9	55.5	62.8	68.8	75.5	81.7	85.0

GLOSSARY OF TERMS

References by Esau (1965), Fahn (1967), and Fuller and Tippo (1949) were used for the definitions below.

Abaxial	Directed outwards from the axis (leaf surface faces away from the stem).
Adaxial	Directed toward the axis (leaf surface faces toward the stem).
Bulliform cell	An enlarged epidermal cell occurring in longitudinal rows of similar cells in the _Gramineae_. It is thought to play a role in the rolling and unrolling of leaves.
Chlorenchyma	Chloroplast-containing parenchyma tissue.
Compact leaf	Leaf, as corn (_Zea mays_ L.), with a mesophyll comprised of relatively compact chlorenchyma with few intercellular spaces (non-porous mesophyll).
Cuticle	A layer of fatty substance, cutin, on the epidermal outer cell walls that is almost impermeable to water.
Dorsiventral leaf	A leaf with palisade parenchyma cells on one side of the blade, and spongy parenchyma cells on the other.
Druse	A globular compound crystal with many component crystals projecting from its surface.
Epidermis	The outer cellular layer of a leaf, primary in origin; if multiseriate (multiple epidermis) only the outer layer differentiates epidermal characteristics.
Genus (plural genera)	A group of closely related species. In the binomial system of nomenclature, the generic name usually refers to some distinctive character of a plant and the species name is descriptive of a plant. Related species constitute a genus and related genera constitute a family.

Intercellular space	Space among cells within the leaf.
Isolateral leaf	A leaf having palisade parenchyma cells on both sides of the blade.
Lysigenous space	An intercellular space that originated by cell wall dissolutions.
Lacuna (pl. lacunae)	Air space.
Mesophyll	Parenchyma tissue of a leaf between the epidermal layers.
Multiseriate	Consisting of many layers of cells.
Nectary	A multicellular glandular structure in leaves that secretes a sugary liquid.
Palisade parenchyma layer	Parenchyma layer of a leaf mesophyll whose cells have an elongated form (palisade cells) perpendicular to the leaf surface.
Paradermal (tangential)	Refers to a section made parallel with the surface of a leaf.
Parenchyma cell	Thin-walled cell found in leaves that is capable of growth and division.
Pubescent	Covered with hairs.
Sclerenchyma	Thick-walled cells whose principal function is strengthening plant parts. Sclerenchyma cells may or may not have a protoplast at maturity.
Spongy parenchyma layer	Parenchyma layer of a leaf mesophyll with conspicuous intercellular spaces (porous mesophyll).
Storage cells	Large thin-walled cells used for storage of water and mucilages.
Succulent leaf	Fleshy-type leaves (malacophyllous) with many cells that store water and mucilages.
Transection	See transverse.
Transverse	A cross section. A section taken perpendicular to the longitudinal axis of the cell. Also called transection.

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